

1003 Reg/PCT/PTO/20 JAN 2002

FORM PTO-1390 (REV. 5-93)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY'S DOCKET NUMBER <b>10191/2169</b>	
<b>TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371</b>				U.S. APPLICATION NO. (If known, see 37 CFR 1.5) <b>10/031842</b>	
INTERNATIONAL APPLICATION NO <b>PCT/DE00/01836</b>		INTERNATIONAL FILING DATE <b>6 June 2000 (06.06.00)</b>		PRIORITY DATE CLAIMED: <b>20 July 1999 (20.07.99)</b>	
TITLE OF INVENTION <b>DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING AN INDUCTIVELY COUPLED PLASMA</b>					
APPLICANT(S) FOR DO/EO/US <b>Volker BECKER, Franz LAERMER, and Andrea SCHILP</b>					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information					
1. <input checked="" type="checkbox"/> This is a <b>FIRST</b> submission of items concerning a filing under 35 U.S.C. 371.					
2. <input type="checkbox"/> This is a <b>SECOND</b> or <b>SUBSEQUENT</b> submission of items concerning a filing under 35 U.S.C. 371.					
3. <input checked="" type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)) immediately rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).					
4. <input checked="" type="checkbox"/> A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date					
5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371(c)(2))					
a. <input type="checkbox"/> is transmitted herewith (required only if not transmitted by the International Bureau).					
b. <input checked="" type="checkbox"/> has been transmitted by the International Bureau					
c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US)					
6. <input checked="" type="checkbox"/> A translation of the International Application into English (35 U.S.C. 371(c)(2)).					
7. <input checked="" type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))					
a. <input type="checkbox"/> are transmitted herewith (required only if not transmitted by the International Bureau)					
b. <input type="checkbox"/> have been transmitted by the International Bureau					
c. <input type="checkbox"/> have not been made, however, the time limit for making such amendments has NOT expired					
d. <input checked="" type="checkbox"/> have not been made and will not be made.					
8. <input type="checkbox"/> A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).					
9. <input checked="" type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)) (unsigned).					
10. <input type="checkbox"/> A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).					
<b>Items 11. to 16. below concern other document(s) or information included:</b>					
11. <input checked="" type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98.					
12. <input type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.					
13. <input checked="" type="checkbox"/> A <b>FIRST</b> preliminary amendment.					
14. <input checked="" type="checkbox"/> A substitute specification and marked-up version.					
15. <input type="checkbox"/> A change of power of attorney and/or address letter					
16. <input checked="" type="checkbox"/> Other items or information. International Search Report (translated), International Preliminary Examination Report (translated) and PCT/RO/101.					

EXPRESS MAIL NO : EL244510538

531 Rec'd PCT 82 JAN 2002

U.S. APPLICATION NO. <u>10/031842</u> 37 C.F.R. 1.5		INTERNATIONAL APPLICATION NO PCT/DE00/01836		ATTORNEY'S DOCKET NUMBER 10191/2169	
<p>17. <input checked="" type="checkbox"/> The following fees are submitted:</p> <p><b>Basic National Fee (37 CFR 1.492(a)(1)-(5)):</b> Search Report has been prepared by the EUROPEAN PATENT OFFICE or JPO ..... \$890.00</p> <p>International preliminary examination fee paid to USPTO (37 CFR 1.482) ..... \$710.00</p> <p>No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2)) ..... \$740.00</p> <p>Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... \$1,040.00</p> <p>International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) ..... \$100.00</p>				<p><u>CALCULATIONS</u>   <u>PTO USE ONLY</u></p>	
ENTER APPROPRIATE BASIC FEE AMOUNT =				\$ 890	
Surcharge of \$130.00 for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(e)).				\$	
Claims	Number Filed	Number Extra	Rate		
Total Claims	35 - 20 =	15	X \$18.00	\$ 270	
Independent Claims	2 - 3 =	0	X \$84.00	\$ 0	
Multiple dependent claim(s) (if applicable)			+ \$280.00	\$	
TOTAL OF ABOVE CALCULATIONS =				\$ 1160	
Reduction by 1/2 for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 CFR 1.9, 1.27, 1.28)				\$	
SUBTOTAL =				\$ 1160	
Processing fee of \$130.00 for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				+	\$
TOTAL NATIONAL FEE =				\$ 1160	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). \$40.00 per property.				+	\$
TOTAL FEES ENCLOSED =				\$1160	
				Amount to be refunded	\$
				charged	\$
<p>a. <input type="checkbox"/> A check in the amount of \$_____ to cover the above fees is enclosed</p> <p>b. <input checked="" type="checkbox"/> Please charge my Deposit Account No. <u>11-0600</u> in the amount of \$ <b>1160.00</b> to cover the above fees. A duplicate copy of this sheet is enclosed</p> <p>c. <input checked="" type="checkbox"/> The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. <u>11-0600</u>. A duplicate copy of this sheet is enclosed</p> <p><b>NOTE:</b> Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.</p>					
SEND ALL CORRESPONDENCE TO: Kenyon & Kenyon One Broadway New York, New York 10004			<p><u>Richard L. Mayer</u> (Reg. No. 42,194) <i>for</i></p> <p>SIGNATURE</p> <p>Richard L. Mayer, Reg. No. 22,490</p> <p>NAME</p> <p><u>January 22, 2002</u></p> <p>DATE</p>		
CUSTOMER NO. 26646					

10031842 .061002  
10/031842  
531 Rec'd PCT/P. 22 JAN 2002  
[10191/2169]

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

Inventor(s) : Volker BECKER et al.  
Serial No. : To Be Assigned  
Filed : Herewith  
For : DEVICE AND METHOD FOR ETCHING A SUBSTRATE  
BY USING AN INDUCTIVELY COUPLED PLASMA  
Examiner : To Be Assigned  
Art Unit : To Be Assigned

Assistant Commissioner for Patents  
Washington, D.C. 20231

**PRELIMINARY AMENDMENT AND  
37 C.F.R. § 1.125 SUBSTITUTE SPECIFICATION STATEMENT**

S I R:

Kindly amend the above-captioned application before examination, as  
set forth below.

**IN THE SPECIFICATION AND ABSTRACT:**

In accordance with 37 C.F.R. § 1.121(b)(3), a Substitute Specification  
(including the Abstract, but without claims) accompanies this response. It is  
respectfully requested that the Substitute Specification (including Abstract) be  
entered to replace the Specification of record.

**IN THE CLAIMS:**

On the first page of the claims, first line, change "What is claimed is:"  
to --WHAT IS CLAIMED IS:--.

Please cancel, without prejudice, claims 1 to 32 in the underlying PCT  
application.

Please add the following new claims:

--33. (New) A device for etching a substrate, comprising:

an inductively coupled plasma source configured to generate a high-frequency electromagnetic alternating field;

a reactor configured to produce an inductively coupled plasma from reactive particles by the action of the high-frequency electromagnetic alternating field upon a reactive gas; and

a first arrangement configured to produce a magnetic field between the substrate and the inductively coupled plasma source, the magnetic field one of static and time-wise varying.

34. (New) The device according to claim 33, wherein the substrate includes a silicon element.

35. (New) The device according to claim 33, wherein the first arrangement surrounds the reactor in at least one region between the inductively coupled plasma source and the substrate, a wall of the reactor formed in the region by a spacer.

36. (New) The device according to claim 33, wherein the first arrangement includes one of a magnetic field coil having an appertaining current supply unit and a permanent magnet.

37. (New) The device according to claim 36, wherein the magnetic field coil is configured to produce a magnetic field that varies with the current supply unit in at least one of a time-wise and a pulsable manner.

38. (New) The device according to claim 33, wherein the substrate is positioned on a substrate electrode, the substrate electrode configured to be acted upon by a substrate voltage generator with a high-frequency power that is one of continuous, time-varying, and pulsed.

39. (New) The device according to claim 33, wherein an inside of the reactor includes an aperture arranged between the first arrangement and the substrate, the aperture concentric with the reactor wall.

40. (New) The device according to claim 33, further comprising a second arrangement configured to set a plasma power coupled by the inductively coupled plasma source into the inductively coupled plasma via the high-frequency electromagnetic alternating field.

41. (New) The device according to claim 40, wherein the second arrangement includes an inductively coupled plasma coil generator configured to produce a variably adjustable high-frequency power coupled into the plasma as plasma power, the high-frequency power at least one of periodically varied and pulsed.

42. (New) The device according to claim 41, wherein an average plasma power of 300 watt to 5000 watt is coupleable into the inductively coupled plasma using the inductively coupled plasma coil generator.

43. (New) The device according to claim 40, further comprising a second impedance transformer in the form of a balanced symmetrical matching network configured to match an output impedance of the inductively coupled plasma coil generator to a plasma impedance which is a function of the coupled-in plasma power.

44. (New) The device according to claim 43, wherein in response to a predefined maximum plasma power to be coupled into the inductively coupled plasma, the second impedance transformer is preset to ensure an at least largely optimal impedance matching.

45. (New) The device according to claim 41, further comprising components integrated into the inductively coupled plasma coil generator are configured to vary a frequency of the generated electromagnetic alternating field to match an impedance as a function of the plasma power to be coupled in.

46. (New) The device according to claim 45, wherein the inductively coupled plasma coil generator includes an automatically acting feedback circuit having a frequency-selected component.

47. (New) The device according to claim 41, wherein the inductively coupled plasma coil generator includes at least one regulated power element, at least one frequency-selective band-pass filter having a predefined steady-state frequency, and one of a delay line and a phase shifter.

48. (New) The device according to claim 41, wherein the inductively coupled plasma coil generator is connected with at least one of the current supply unit and the substrate voltage generator.

49. (New) A method for etching a substrate using a device having an inductively coupled plasma source configured to generate a high-frequency electromagnetic alternating field and a reactor configured to produce an inductively coupled plasma from reactive particles by the action of the high-frequency electromagnetic alternating field upon a reactive gas, comprising the step of:

producing a magnetic field, during the etching, a direction of which is at least one of approximately and predominantly parallel to a direction defined by a connecting line of the substrate and the inductively coupled plasma;

wherein the magnetic field is at least one of static, time-wise varying, periodically varying and pulsed.

50. (New) The method according to claim 49, wherein the substrate includes a silicon element.

51. (New) The method according to claim 49, wherein the magnetic field extends into a region of the substrate and the inductively coupled plasma.

52. (New) The method according to claim 49, wherein the magnetic field is produced in the producing step using an amplitude of a field strength between 10 mTesla and 100 mTesla on an inside of the reactor.

53. (New) The method according to claim 49, wherein the inductively coupled plasma is produced with a high-frequency electromagnetic alternating field having a frequency that is one of constant and varying within a frequency range about a steady-state frequency.

54. (New) The method according to claim 53, wherein the steady-state frequency is 13.56 MHz.

55. (New) The method according to claim 49, wherein the etching is performed in alternating etching and passivating steps.

56. (New) The method according to claim 49, wherein the etching is performed at a process pressure of 5  $\mu$ bar to 100  $\mu$ bar and a coupled-in average plasma power of 300 watt to 5000 watt.

57. (New) The method according to claim 49, wherein a pulsed magnetic field is produced, via a current supply unit, an amplitude of field strength of which, on an inside of the reactor, is between 10 mTesla and 100 mTesla.

58. (New) The method according to claim 57, wherein the magnetic field is pulsed at a frequency of 10 Hz to 20 kHz, and a pulse/pause ratio of 1:1 to 1:100 is set.

59. (New) The method according to claim 49, wherein a variably adjustable high-frequency power is produced, is coupled as plasma power into the inductively coupled plasma, and is at least one of periodically varied and pulsed.

60. (New) The method according to claim 59, further comprising the step of operating an inductively coupled plasma coil generator having a frequency of 10 Hz to 1 MHz in a pulsed fashion to produce the plasma power, an average plasma power of 300 watt to 5000 watt coupled into the inductively coupled plasma.

61. (New) The method according to claim 60, wherein the inductively coupled plasma coil generator is operated using a pulse/pause ratio of 1:1 to 1:100.

62. (New) The method according to claim 59, wherein the pulsing of the coupled-in plasma power is accompanied by a change in frequency of the coupled-in high-frequency power.

63. (New) The method according to claim 62, further comprising the step of controlling the frequency change to maximize the plasma power coupled into the inductively coupled plasma during pulsing.

64. (New) The method according to claim 62, wherein the inductively coupled plasma coil generator is operated in the form of an automatically acting feedback circuit, and a frequency of the high-frequency power produced, which forms the coupled-in high-frequency electromagnetic alternating field, is varied about the steady-state frequency.

65. (New) The method according to claim 49, wherein the pulsing of the magnetic field is one of correlated in time and synchronized with the pulsing of at least one of the coupled-in plasma power and the high-frequency power coupled into the substrate via the substrate voltage generator.

66. (New) The method according to claim 65, wherein the synchronization is performed so that the magnetic field is first applied before a high-frequency power pulse of the inductively coupled plasma coil generator for the coupling of the plasma power into the inductively coupled plasma, and the magnetic field is only switched off again after the high-frequency power pulse has faded out.

67. (New) The method according to claim 65, wherein a pulse/pause ratio of the magnetic field pulses is greater than a pulse/pause ratio of the high-frequency power pulses, and the magnetic field is held at least approximately constant during the high-frequency power pulses.--.



**REMARKS**

This Preliminary Amendment cancels, without prejudice, claims 1 to 31 in the underlying PCT Application No. PCT/DE00/01836. This Preliminary Amendment adds new claims 32 to 67. The new claims, inter alia, conform the claims to U.S. Patent and Trademark Office rules and does not add any new matter to the application.

In accordance with 37 C.F.R. § 1.121(b)(3), the Substitute Specification (including the Abstract, but without the claims) contains no new matter. The amendments reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. §§ 1.121(b)(3)(iii) and 1.125(b)(2), a Marked Up Version of the Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. Approval and entry of the Substitute Specification (including Abstract) is respectfully requested.

The underlying PCT Application No. PCT/DE00/01836 includes an International Search Report, dated November 22, 2000, a copy of which is included. The Search Report includes a list of documents that were considered by the Examiner in the underlying PCT application.

The underlying PCT Application No. PCT/DE00/01836 also includes an International Preliminary Examination Report, dated September 7, 2001. An English translation of the International Preliminary Examination Report is included herewith.

It is respectfully submitted that the subject matter of the present application is new, non-obvious and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully submitted,

KENYON & KENYON

Bu. 102 agst (Reg. No. 41,172)

Dated: 1/22/02

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DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING  
AN INDUCTIVELY COUPLED PLASMA

The present invention relates to a device and a method which  
can be carried out with it, for etching a substrate,  
especially a silicon element, by using an inductively coupled  
plasma, according to the species defined in the independent  
5 claims.

Background Information

In order to implement an anisotropic high rate etching method,  
for instance, for silicon, using an inductive plasma source,  
10 it is necessary in one method, known, for example, from DE 42  
41 045 C2, to carry out efficient sidewall passivation in as  
short a time as possible, during so-called passivating steps,  
and furthermore to achieve as high a concentration as possible  
15 of silicon-etching fluorine radicals during so-called etching  
steps. Here, in order to achieve an etching rate that is as  
high as possible, it is obvious to work with as high as  
possible an high-frequency power at the inductive plasma  
source, and thereby to couple in as high as possible plasma  
20 powers into the generated inductively coupled plasma.

However, there are limits to these high-frequency powers,  
which result on the one hand from load capacity of the  
electrical components of the plasma source, but, on the other  
25 hand, are also of a process technology nature. Thus,  
high-frequency powers of an inductive plasma source reinforce  
harmful electrical intervention by the source region in the  
inductively coupled plasma generated, which deteriorate the  
etching results on the substrate wafer.

Also, in etching processes according to the kind in DE 42 41  
045 C2, stability problems appear in the coupling in of the  
30

plasma in the changeover phases between etching and passivating steps. This is based on the fact that, in response to high power to be coupled in, in the kwatt range, power reflection and overvoltage appearing during the changeover phases can have a destructive effect on the electrical circuit of the plasma source (coil, connected capacitors, generator output stage).

On this point, German Application DE 199 00 179 describes an inductive plasma source, further refined compared to the one in DE 42 41 045 C2, which, with the aid of a loss-free symmetrical high-frequency supply of the coil of the inductive plasma source, is suitable for especially high plasma powers, and generates an inductive plasma which is particularly poor in electrical interference induced voltages. But for this source type too there exists a practicable power limit of about 3 kwatt to 5 kwatt, above which the required high-frequency components become extremely expensive, or, with respect to plasma stability, problems take the upper hand.

A possible approach towards attaining higher etching rates within a manageable power scope is to raise the efficiency of the plasma generation. In this connection, using magnetic fields to raise plasma efficiency is known in principle from the related art.

By applying a magnetic field to a plasma, as is well known, the electron paths in the plasma are bent, and because of that the residence time of the electrons in the plasma is increased, i.e. the time until they reach a wall which absorbs the electrons, so that each electron can interact more often with surrounding gas atoms until it leaves the effective plasma excitation region. Such impact interactions between electrons and gas molecules lead to the desired ionization or dissociation of the gas molecules along with the release of radicals needed for the etching process.

According to the related art, a so-called "multipole confinement" includes a metallic, nonferromagnetic wall having a plurality of permanent magnets of alternating polarity, which reflects electrons from the wall outfitted with these magnets, by the action of magnetic fields. Thereby, a higher electron density can be generated within this "multipole confinement". An analogous RIE (reactive ion etching) source is marketed, for example, by TEGAL Corporation, Petaluma CA 94955-6020, USA, as a so-called "HRe<sup>-</sup> Source".

Other known plasma source types further make use of a magnetic field having a field direction parallel to a substrate electrode. Thus, by using a kind of Helmholtz coil pair directly at the substrate electrode, a field distribution is generated that is as homogeneous as possible, which leads there to increased length of the electron paths, and thereby to the generation of greater plasma densities. For the further homogenization of the effects, this horizontally oriented magnetic field, as, for example, in the MRIE (magnetically enhanced reactive ion etching) equipment of Allied Materials, Inc., Santa Clara CA 95054-3299, USA, can further be rotated slowly in a planar manner.

In the case of so-called ECR (electron cyclotron resonance) sources, it is further already known that one should tune a longitudinal magnetic field in such a way that the circulation frequency of the electrons in this magnetic field, the so-called cyclotron frequency, is resonant with the frequency of the coupled in microwave radiation, at least in a certain volume range of the etching reactor. Thus, an especially efficient plasma excitation by microwave irradiation can take place at a sufficiently free path length of the electrons, which opens up to such ECR sources the low-pressure range of process pressures lower than 1  $\mu$ bar as a field of application. In this connection, the low pressure is a necessary condition for a sufficiently great path length of the electrons and for efficient plasma excitation. At higher pressures, ECR sources

rapidly become inefficient, and go over to an unwanted thermal plasma generation. The advantage of the magnetic inclusion and the resonant excitation are thereby lost to a considerable extent.

5

It follows from the formula for the cyclotron frequency  $\omega = eB/m$  that  $B = m\omega/e$ , i.e. at the usually irradiated microwave frequency of 2.45 GHz the magnetic field strength required for cyclotron resonance is 87.6 mTesla.

10

This application is not simply transferable to the case of high-frequency excitation in the MHz range, i.e. the case of typical frequencies for ICP (inductively coupled plasma) sources, since the free path lengths of the electrons, required for this, assume extremely low, impracticable pressures. After all, an inductive plasma source for high rate etching methods has to be configured for a relatively high pressure range of ca 30 to 100  $\mu$ bar.

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20

The usual high frequency of 13.56 MHz, used for inductive plasma excitation using ICP sources, would further, in the case of cyclotron resonance, imply a resonance field strength of only 0.5 mT. However, such a low field hardly has any remaining guidance function for the electrons. For a sufficient guidance function, i.e. suppression of wall losses of the electrons in an extended plasma volume, field strengths of 10 mTesla or rather several times 10 mTesla to 100 mTesla are required.

25

30

Magnetic coils in an ECR-type configuration are also usually placed above, or at the same height as the plasma source, so as to generate the greatest field strength directly at the location of plasma generation, and so as to have the greatest possible influence on the plasma generating mechanism there.

35

In the direction of the substrate to be etched, then, the magnetic field strength decreases rapidly because of the divergence of the magnetic field, so that the guidance

function of the magnetic field is no longer sufficiently present in such an arrangement.

Varying plasma power coupled in an inductively coupled plasma  
5 having a high-frequency electromagnetic alternating field, adiabatically, between individual method steps, especially alternating etching and passivating steps, is further known from German Application DE 199 198 32. Such an adiabatic power transition, i.e. a gradual running-up or lowering of the  
10 coupled-in plasma power along with simultaneous continuous matching of the impedance of the ICP source to the respective plasma impedance as a function of the coupled-in plasma power, with the aid of an automatic matching network or an impedance transformer ("matchbox"), makes it possible to control the  
15 explained problems with regard to power reflection and voltage magnification in response to switching on and off plasma powers in the range of 1 kwatt to 5 kwatt. However, in this connection, a typical duration of transient effects lies in the range of 0.1 sec to 2 sec. Therefore, power changes cannot  
20 be made by this approach.

#### Summary of the Invention

Compared to the related art, the device according to the  
25 present invention has the advantage that it makes available a plasma etching equipment having inductive plasma generation or a plasma inductively coupled via an ICP source, in which an additional constant magnetic field, or one varying with time, considerably increases the efficiency of plasma generation. In  
30 this connection, the inductively coupled plasma generated, starting from the plasma source, is guided through the generated magnetic field in a kind of magnetic bottle to a substrate to be etched. For this purpose, a magnetic field coil or a sufficiently strong permanent magnet having  
35 longitudinal field direction is placed between the inductive plasma source (ICP source) and the substrate or a substrate electrode carrying the substrate, such as a silicon wafer.

Thus, when carrying out the method according to the present invention, this device effects a very efficient plasma generation in the area of inductive excitation, and a low-loss plasma transport right up to the substrate to be etched. At the same time, decoupling of plasma generation and the generation of the magnetic field is achieved. Because of the symmetry of the design of the device according to the present invention, in spite of the nonhomogeneous field distribution of the magnetic coil, good uniformity on the substrate surface continues to be maintained.

All in all, by using the generated longitudinal magnetic field, i.e. a magnetic field whose direction is at least approximately or predominantly parallel to the direction defined by the connecting line from the substrate to the inductively coupled plasma, the high-frequency power at the ICP source, required for high rate etching at the highest etching rates, is thus clearly reduced by efficient utilization of the coupled-in high-frequency power for generating the desired plasma species (electrons, ions, free radicals). Because of this, clearly higher etching rates are possible at equal plasma power.

Because the generation of the longitudinal magnetic field is placed between the ICP source and the substrate, both the substrate and the area of plasma generation in the reactor are in a region of relatively high magnetic field strengths, and, thus, of good guidance of the electrons and ultimately also the ions.

In addition, electrical interference effects coming from the source region can be effectively reduced by the improvement, achieved with the device according to the present invention, of the economics of the ICP source and the possibility, that goes with it, of reducing power without reducing the etching rate, or with etching rate increase at equal plasma power. On the whole, therefore, the etching result is achieved more



economically.

Furthermore, a power that is constant, pulsed or generally  
varying with time can be made available considerably more  
5 cost-effectively than a greater high-frequency power for  
coupling in the plasma. This power, by the way, demonstrates  
no harmful effect on the etching process or components of the  
plasma etching equipment.

10 Advantageous further refinements of the present invention  
result from the measures indicated in the dependent claims.

Thus, a particularly advantageous configuration of the device  
according to the present invention comes about if an aperture  
15 is additionally provided, positioned concentrically with the  
inner wall of the reactor, which is preferably arranged ca  
5 cm above the substrate positioned on a substrate electrode.  
Such an aperture construction is known, for example, from  
German patent DE 197 34 278.

20 It is also advantageous if the plasma etching equipment  
according to the present invention is furnished with a  
balanced, symmetrically designed and symmetrically supplied  
configuration of the ICP source, as is proposed in German  
25 Application DE 199 00 179.

A magnetic field coil having an appertaining current supply  
unit is particuLarly suitable for generating the magnetic  
field, since with that, the generated magnetic field is  
30 timely, and, with regard to its strength, is variable and, in  
particular, pulsable.

It is also advantageous if an ICP coil generator is provided,  
which generates a variably adjustable, especially periodically  
35 varying or pulsed high-frequency power, which can be coupled  
into the inductively coupled plasma as plasma power.

It is also very advantageous if components are integrated into the ICP coil generator which carry out a variation of the frequency of the generated electromagnetic alternating field, for adapting the impedance as a function of the plasma power to be coupled in. An automatically acting feedback circuit having a frequency-selective component along the lines of a Meissner oscillator is particularly advantageously suitable for this.

Finally, it is very advantageous if the pulsing of the generated magnetic field is correlated in time or synchronized with the pulsing of the coupled-in plasma power and/or the pulsing of the high-frequency power coupled into the substrate via the substrate voltage generator.

#### Brief Description of the Drawings

Exemplary embodiments of the present invention are explained in detail in the following description, using the drawings.

The Figures show:

- Figure 1 a very schematic plasma etching equipment,
- Figure 2 an electronic feedback circuit having a connected ICP source,
- Figure 3 an example of a filter characteristic curve, and
- Figure 4 an example of a correlation in time of high frequency power pulses and magnetic field pulses.

#### Exemplary Embodiments

A first exemplary embodiment of the present invention is explained in detail with reference to Figure 1. A plasma etching equipment 5 first of all has a reactor 15, in whose upper region an inductively coupled plasma 14 is generated in a manner known per se, via an ICP (inductively coupled plasma) source 13. The following are also provided here: a gas feed 19 for supplying a reactive gas such as  $\text{SF}_6$ ,  $\text{ClF}_3$ ,  $\text{O}_2$ ,  $\text{C}_4\text{F}_8$ ,  $\text{C}_3\text{F}_6$ ,

SiF<sub>4</sub> or NF<sub>3</sub>, a gas discharge 20 for removing reaction products, a substrate 10 such as a silicon body or a silicon wafer to be structured by the etching method according to the present invention, a substrate electrode 11 which is in contact with substrate 10, a substrate voltage generator 12 and a first impedance transformer 16. Substrate voltage generator 12 also couples in a high frequency alternating voltage or high frequency power into substrate electrode 11 and above that into substrate 10, causing acceleration of ions generated in inductively coupled plasma 14 onto substrate 10. The high-frequency power or alternating voltage input in this way is typically between 3 watts and 50 watts and 5 volts and 100 volts in continuous operation and in pulsed operation respectively, each averaged over time over the pulse sequence.

In addition, an ICP coil generator 17 is also provided, which is connected to a second impedance transformer 18, and above that with ICP source 13. Thus, ICP source 13 generates a high-frequency electromagnetic alternating field and also an inductively coupled plasma 14 composed of reactive particles and electrically charged particles (ions) formed by the action of the high-frequency electromagnetic alternating field on the reactive gas in reactor 15. ICP source 13 has a coil for this having at least one winding.

Second impedance transformer 18 is preferably designed in the manner described in German Patent 199 00 179, so that a balanced symmetrical designed configuration and supply of ICP source 13 over ICP coil generator 17 are obtained. This guarantees in particular that the high-frequency alternating voltages applied to the two ends of the coil of ICP source 13 are at least approximately in phase opposition to each other. Furthermore, the center tap of the coil of the ICP source is preferably grounded, as indicated in Figure 2.

The anisotropic high-rate etching process for silicon, having alternating etching and passivating steps, known from DE 42 41

045 C2, is further carried out, for example, using plasma etching equipment 5. With respect to further details, known per se to one skilled in the art, concerning plasma etching equipment 5, as described up to this point as being known from the related art, and the etching method carried out with it, especially with respect to the reactive gases, the process pressures and the substrate electrode voltages in each respective etching step or passivating step, as the case may be, we therefore refer to DE 42 41 045 C2.

10

Plasma etching equipment 5, by the way, is also suitable for supervisory control, as described in German Application DE 199 27 806.7.

15 During the etching of substrate 10, in particular during the passivating steps in reactor 15, passivating is carried out at a process pressure of 5  $\mu$ bar to 20  $\mu$ bar, and a plasma power, coupled into plasma 14 via ICP source 13, of 300 to 1000 Watt.  $C_4F_8$  or  $C_3F_6$ , for example, are suitable as passivating gases.

20 During the subsequent etching steps, etching is done at a process pressure of 30  $\mu$ bar to 50  $\mu$ bar and a high plasma power of 1000 to 5000 Watt.  $SF_6$  or  $ClF_3$ , for example, are suitable as reactive gas.

25 A preferred embodiment of the plasma etching equipment further provides that, to improve the selectivity of an etching base polymer removal relative to the sidewall film removal, the ion acceleration voltage applied to the substrate by substrate voltage generator 12 be switched back by reduction of the  
30 coupled-in plasma power in the etching steps, each time after breakthrough of the initial etching base polymer, as has been proposed in German Application DE 199 19 832 and explained in detail.

35 This switching back here takes place in a manner known per se, either abruptly or continuously via a time-related ramp function. This achieves a further improvement of the silicon

etching rate, of the selectivity of the etching process with respect to a masking material, the profile accuracy and, for example suppression of pockets in a dielectric etch-stop layer.

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In addition, according to the present invention, a so-called "spacer" is further placed as spacer 22, made of a nonferromagnetic material such as aluminum, between inductively coupled plasma 14 or ICP source 13, i.e. The actual plasma excitation zone, and substrate 10. This spacer 22 is concentrically set into the wall of reactor 15 as spacer ring, and thus forms the reactor wall, from place to place. It has a typical height of ca 5 mm to 30 mm at a typical diameter of reactor 15 of 30 to 100 cm.

15

Spacer 22 further surrounds a magnetic field coil 21, which has, for instance, 100 to 300 turns and is wound with a lacquered copper wire of a sufficient gauge for the strength of current to be used. Additionally, copper pipes can be accommodated in magnetic field coil 21, having cooling water flowing through them so as to remove heat losses from magnetic field coil 21.

25

Alternatively, it is also possible to wind magnetic field coil 21 itself from a thin copper pipe lacquered with an electrically insulating material, and having the cooling water flowing through it directly.

30

An electric current such as 10 to 100 amp is conducted through magnetic field coil 21 via a current supply unit 23.

35

In the explained first exemplary embodiment this is, for example, a d.c. current which generates a static magnetic field on the inside of reactor 15, which, in the case of a magnetic field coil 21 having 100 turns and a length of 11 cm as well as a diameter of 40 cm generates a magnetic field strength in the center of magnetic field coil 21 of about 0.3

mTesla/A of current flow.

For a significant increase of plasma generating efficiency and sufficient magnetic guidance of inductively coupled plasma 14, 10 mT to 100 mT, for instance 30 mT, are required, as has already been explained. That means, that current supply unit 23 makes available current strengths of about 30 to 100 amp during etching of a substrate 10, using plasma etching equipment 5.

Instead of magnetic field coil 21, by the way, a permanent magnet can be used. Such a permanent magnet advantageously requires no energy, but has the disadvantage that setting the magnetic field strength, which is of advantage for setting an optimum etching process, is not possible. Besides, the field strength of a permanent magnet is temperature dependent, so that magnetic field coil 21 is preferred.

It is important in each case that the direction of the magnetic field generated by magnetic field coil 21 or by the permanent magnet is at least approximately or predominantly parallel to the direction defined by the connecting line of substrate 10 and inductively coupled plasma 14 or the plasma generating zone (longitudinal magnetic field orientation).

An advantageous refinement of the explained exemplary embodiment further provides for installing an aperture known from DE 197 34 278, for improvement of the uniformity of the etching process. For reasons of clarity, this aperture is omitted in Figure 1. It is mounted on the inside of reactor 15, concentrically with the reactor wall, between ICP source 13 or the plasma excitation zone and substrate 10. It is preferably fastened on spacer 22, ca 5 cm above substrate electrode 11 or substrate 10.

Also, in case of the use of a magnetic field coil 21, a suitable monitoring device, known per se, has to be integrated

into current supply unit 23, the monitoring device being integrated into the process sequence control, and carrying out monitoring of the coil temperature and emergency switching-off, for example, when there is a shortage of cooling water.

5

In the first exemplary embodiment, during etching, ICP coil generator 17 couples continuously during the etching steps or the passivating steps an at least to a great extent constant plasma power of a minimum of 300 Watt to a maximum of 5000 Watt into inductively coupled plasma 14.

10

In particular, during the passivating steps, a plasma power of 500 Watt is coupled into inductively coupled plasma 14, and during the etching steps a plasma power of 2000 Watt is coupled into inductively coupled plasma 14; ICP coil generator and second impedance transformer 18, in the manner known from DE 199 198 32 and explained above, in response to a transition from a passivating to an etching step, carrying out an adiabatic up-regulating of the coupled-in plasma power over a time-related ramp function and, at the same time, via second impedance transformer 18, an automatic, stepwise or continuous impedance adaptation.

15

20

A second exemplary embodiment of the present invention provides that, as a modification of the first exemplary embodiment, instead of adiabatic control of the high-frequency power coupled into the inductively coupled plasma 14 by IPC source 13, and instead of a matching of the coupled-in high frequency power given at any point in time, via the automatic matching network ("matchbox") as the second impedance transformer 18, to the plasma impedance changing with increasing plasma power, alternatively the previously constant frequency of the high frequency electromagnetic alternating field, which ICP coil generator 17 produces, should be varied for impedance matching.

30

35

The matchbox, preferably symmetrically designed and supplying ICP source 13 symmetrically in second impedance transformer 18 is, in this connection, preferably set in such a way that it ensures an optimum impedance matching in the steady-state power case. This steady-state power case is characterized in that, in this connection, the plasma power inductively coupled into plasma 14 has reached a high maximum or final value such as 3000 watt to 5000 watt, a steady-state frequency or a resonant frequency 1'' of, for example, 13.56 MHz of the frequency produced by ICP coil generator 17 of the high frequency electromagnetic alternating field having simultaneously been reached.

The steady-state frequency 1'' of customary ICP coil generators 17 is generally 13.56 MHz, besides this standard, generators having other frequencies or frequency ranges also being commercially obtainable. However, in such ICP coil generators 17, in deviation from the realization according to the present invention, the steady-state frequency 1'' is set to a fixed value which is, for example, derived with great accuracy from the natural frequency of a quartz-crystal oscillator. Thus, during a power change, for example, during the run-up of the plasma power to be coupled into plasma 14 from, for instance 500 watt to 3000 watt at a steady frequency of the high-frequency of high-frequency alternating field generated by ICP coil generator 17, with a predefined setting of impedance transformer 17, no matching, or only a bad one, to the plasma impedance changing as a function of the plasma power is possible, so that high reflected powers appear during the transients. However, if the frequency of ICP coil generator 17 is enabled in such phases, then by a change in the frequency of the high-frequency electromagnetic alternating field, a substantially optimum impedance adaptation, even under quickly changing plasma conditions, can be maintained.

The essential advantage of the production of the correct



impedance matching via a variable frequency of the high-frequency power of coil generator 17 is that this frequency change can be carried out very fast because it is limited only by the control rate of the corresponding electronic circuit. That makes possible reaction times in the microsecond range, without any problem.

In contrast to that, manual or automatic setting of an matching network requires the change of mechanical quantities in second impedance transformer 18, for example the resetting of variable capacitors by motors, which takes place correspondingly slowly. Typical time constants here lie in the range of tenths of seconds.

In a preferred design of the second exemplary embodiment, a control circuit integrated in second impedance transformer 18, for example, in a manner known per se, detects the instantaneous control error, i.e. the faulty adaptation of the impedance of the output of ICP coil generator 17 and the impedance of ICP source 13, with respect to amplitude and phase. This takes place preferably by a measurement of the signal reflected at ICP source 13 or second impedance transformer 18, using reflectometers sufficiently known from high-frequency technology, amplitude and phase errors being detected.

From this information, a corresponding frequency change of the electromagnetic alternating field at ICP coil generator 17, required in each case, is ascertained, preferably continuously within a predefined frequency range, so that the control errors with respect to amplitude and phase can be minimized. This basically only corrects an amplitude error, since, as is well known, to a great extent only the real plasma resistance changes as a function of the coupled in plasma power, and the phase relationship of the impedances is set correctly, at least roughly, just by the explained presetting of second impedance transformer 18.

When the output power of ICP coil generator 17, and with that also the plasma impedance finally become steady-state after completion of the run-up of the plasma power, the control circuit takes the frequency of ICP coil generator 17, or of  
5 the electromagnetic alternating field generated, back to the actually desired fixed value such as 13.56 MHz, and fixes it there. In this connection, for the frequency in the case of the steady-state power, second impedance transformer 18 is set correctly via the presetting ascertained before, which, of  
10 course, is a function of the maximum plasma power to be reached, and this can be done either manually or automatically, using low-speed control characteristics.

To sum up, if the frequency of ICP coil generator 17 is thus  
15 fixed, in the steady-state case of the power to be coupled in, at, for example, 13.56 MHz, whereas, during the course of the unstable run-up phases of the generator output power, the frequency is temporarily released within a certain bandwidth, and is controlled by an electronic control system for  
20 impedance matching. Thus it is possible to carry out even very fast power changes of the generator output power in the range of microseconds in a stable manner, at simultaneous high power changes, which is not possible using known matching networks or impedance transformers.

25 This is explained, for example, with the aid of Figure 3, in which a filter characteristic line 1' is represented, which shows a preset frequency range within which the frequency of ICP coil generator 17 may be varied, each frequency being  
30 assigned a certain high-frequency power or plasma power to be coupled in, or a coupling loss A of the power of ICP coil generator 17. The frequency to be reached in the case of steady-state power, in this connection, is the steady-state frequency 1'', which may be 13.56 MHz, for example, and at  
35 which the predefined maximum power is supplied as the plasma power to inductively coupled plasma 14.

An especially preferable third exemplary embodiment of the present invention, in continuation of the second exemplary embodiment explained above, further provides leaving the frequency variation of ICP coil generator 17 to an  
5 automatically acting feedback circuit, so that one can do without measuring the faulty adaptation in each case or measuring the reflected signals, for example, by reflectometer. This is explained in more detail with the aid of Figure 2.

10 In this connection, ICP source 13, i.e. its coil, to be exact, in a manner known per se from DE 199 00 179, is first energized by a preferably balanced symmetrical matching network 2 from an unbalanced unsymmetrical output of ICP coil  
15 generator 17. Adaptation network 2 is a part of second impedance transformer 18.

The ICP coil generator 17 is further, in this case, made like a widespread specific embodiment, including a high-frequency  
20 power element 3 and a quartz oscillator 4 for producing a high-frequency fundamental wave having a fixed frequency such as 13.56 MHz.

In the related art, the high frequency fundamental wave of quartz oscillator 4 is normally supplied to the amplifying  
25 input of power element 3. According to the present invention, however, this supply is modified in such a way that quartz oscillator 4 is made accessible separately from the amplifier input of power element 3, and its input is made accessible  
30 externally, for instance via a corresponding input socket. Since the quartz oscillator in this specific embodiment no longer has a function, it can actually be suitably deactivated.

35 Power element 3 further has generator control inputs 9 in a known way, which are used for external control of ICP coil generator 17. Using them makes possible, for example,

switching on and off ICP coil generator 17 or the stipulation  
of a high frequency power to be generated. In addition,  
generator status outputs 9' are possible, for the feedback of  
generator data such as, for instance, generator status current  
5 output power, reflected power, overload, etc, to an external  
control unit (machine control) not shown, or to current supply  
unit 23 of plasma etching equipment 5.

The amplifier input of power element 3 is now suitably  
10 connected to ICP source 13, in the sense of a feedback circuit  
via a frequency-selective component 1.

In this connection, additionally, capacitors, inductance coils  
and resistors or combinations of these can be interconnected  
15 and provided in a known manner as voltage dividers, in order  
to weaken the high voltages that appear at the coil of ICP  
source 13 to a suitable measure for frequency-selective  
component 1 or the amplifier input of power element 3. Such  
voltage dividers belong to the related art, and are indicated  
20 in Figure 2 only by a decoupling capacitor 24 between the coil  
of ICP source 13 and frequency-selective component 1.

Alternatively, one can also move signal tap 25 to the vicinity  
of the drawn-in grounded center point or center tap 26 of the  
coil of ICP source 13, where correspondingly lower voltage  
25 levels are present. Depending on the distance of the signal  
tap, which, for example, can be designed as an adjustable clip  
contact, from grounded center tap 26 of the coil of ICP source  
13, a larger or smaller tapped voltage can be set, and thus  
favorable level ratios can be achieved.

30 Frequency-selective component 1 is represented in the example  
as a tunable arrangement of coils and capacitors, so-called LC  
resonant circuits, which together form a band-pass filter.  
This band-pass filter has as conducting state region a certain  
35 predefined bandwidth such as 0.1 MHz to 4 MHz, and a filter  
characteristic line 1', as shown as an example in Figure 3.

In particular, the band-pass filter has a resonance or steady-state frequency  $\omega'$  having maximum signal transmission. This steady-state frequency  $\omega'$  is preferably 13.56 MHz and can be fixed exactly, for example, by a quartz-crystal oscillator 6 or a piezoceramic filter element as additional components of the band-pass filter.

Alternatively, it is also possible, instead of LC resonant circuits, to combine so-called piezoceramic filter elements, or other known frequency-selective components known per se, into a band-pass filter having the desired filter characteristic line, bandwidth and steady-state frequency  $\omega'$ .

The set-up described above controlled power element 3, matching network 2, ICP source 13 and band-pass filter represents in total a feedback circuit of the same kind as a Meissner oscillator.

During operation, this first begins to oscillate in the neighborhood of steady-state frequency  $\omega'$ , in order to build up to a predefined output power of power element 3. The phase relationship, required for the build-up, between generator output and signal tap 25 is set correctly for this purpose once, in advance, for example, via a delay line 7 of specific length, and with that, via the phase shift defined by the signal propagation time or a phase shifter instead of delay line 7. This ensures that the coil of ICP source 13 has damping reduced with a correct phase.

Via delay line 7 it is further especially ensured that, at the location of ICP source 13, the driving electrical voltage and the current in the coil of ICP source 13 have a resonance phase of approximately  $90^\circ$  to each other.

In practice, by the way, the resonance condition of the feedback circuit with regard to frequency-selective component 1 is not severe, so that, in general, a small frequency shift

in the neighborhood of resonance or steady-state frequency  $\omega'$  is sufficient for almost automatically correcting the resonance condition with respect to the phase. Therefore it is sufficient to correct the resonance condition only approximately by the outer circuit elements, so that the resonant circuit builds up somewhere close to its steady-state frequency  $\omega'$ .

However, if all phase shifts from signal tap 25 of the coil of ICP source 13 via the band-pass filter into the input of power element 3, and through the power element back to second impedance transformer 18 into the coil of ICP source 13 should sum up so unfavorably that actually dumping instead of damping reduction of the resonant circuit takes place, the system cannot begin to oscillate. The feedback then becomes an unwanted negative feedback instead of the desired positive feedback. The setting of this approximately correct phase is accomplished by delay line 7, whose length should therefore be set at one time in such a way that the feedback acts constructively, i.e. to reduce damping.

All in all, in the case of faulty adaptation to the plasma impedance, for example, during rapid power changes, the explained feedback circuit can thus give way in its frequency within the band pass of the band-pass filter, and always maintain a largely optimum impedance matching, even during rapid impedance changes of inductively coupled plasma 14.

Then, as soon as inductively coupled plasma 14 stabilizes with regard to the plasma impedance or the coupled-in plasma power, the frequency of ICP coil generator 17 will return again to near or exactly the value of the maximum pass frequency, which is given by the resonant frequency or steady-state frequency  $\omega'$ . This matching of the impedance by frequency variation takes place automatically and very rapidly within a few periods of oscillation of the high frequency voltage, i.e. in the microsecond range.

The connection between the output of power element 3 and the input of second impedance transformer 18 is made, by the way, by line 8, which is designed as a coaxial cable, and is capable of carrying a power of a few kwatt.

5

With this automatically building up arrangement, or even with the arrangement described before, having active frequency control for matching to rapidly changing plasma impedances, it is advantageously possible also to perform a pulsed operation of the inductive plasma source.

10

Now, in the case of the refinement of the ICP coil generator described in the fourth exemplary embodiment it is further possible also to perform a pulsed operation of ICP source 13, and thereby, for example, also to couple in pulsing plasma power during the etching or passivating steps of the etching method.

15

To do this, the output power of ICP coil generator 17, for instance, is periodically switched on and off using a repetition frequency of typically 10 Hz to 1 MHz, preferably 10 kHz to 100 kHz, i.e. it is pulsed, or the envelope curve of the output voltage of ICP coil generator 17 has its amplitude modulated by a suitable modulating voltage. Such devices for amplitude modulation are sufficiently well known from high frequency technology.

25

For example, generator control input 9 can be used to select the setpoint value of the high frequency power of ICP coil generator 17 for the purpose of supplying the signal modulating the high frequency power of ICP coil generator 17.

30

Since, in response to a pulsed operation of ICP source 13, very rapid impedance changes appear in plasma 14, according to the related art up to now, it is impossible, especially with power in the kwatt range, to avoid the occurrence of high reflected power during switching on and off coupled-in high

35

frequency power pulses, or at least to make these harmless.

In contrast, by using the device explained in this exemplary embodiment, the impedance matching of inductively coupled  
5 plasma 14, or ICP source 13, and ICP coil generator 17 is ensured at all times, in this case as well.

Compared to a continuous operation, a pulsed operation of ICP  
10 source 13 has the further advantage that, during the high frequency power pulses or during the plasma power pulses a substantially higher plasma density can be achieved than in continuous operation. This is based on the fact that  
generation of an inductive plasma is a high-grade nonlinear  
process, so that the average plasma density in this pulsed  
15 operational mode is higher than in the case of an average plasma power corresponding to the time average.

Therefore, in pulse operation one effectively obtains more reactive species and ions with respect to the time average  
20 than in continuous operation. This is true especially when so-called "giant impulses" are used, i.e. relatively brief and extremely high-powered high frequency power impulses such as 20 kwatt peak power, as is now possible with the device according to the present invention, the average plasma power  
25 at time average being then, for example, only 500 watt.

In this connection, unavoidable heat losses in ICP coil generator 17 and other equipment components of plasma etching equipment 5 are then correlated with the relatively low  
30 time-averaged value of the plasma power, whereas desired plasma effects, particularly the achievable etching rates, advantageously correlate with the occurring peak powers. As a result, the efficiency of generation of reactive species and ions is clearly improved.

35 In this connection, of course, ICP coil generator 17 and the remaining components of plasma etching equipment 5 involved



have to be designed in such a way that they can process even the occurring peak loads (peak currents and peak voltages) without damage. On account of the high voltage peaks at the inductive coil, the balanced supply of the ICP coil has an especially advantageous effect on obtaining favorable plasma properties.

A further considerable advantage of pulsed operation of ICP source 13 is that interfering electrical charges on substrate 10 to be etched can be discharged during the pauses between the high frequency power pulses, and profile control during etching can thereby be improved in toto.

Typical pulse/pause ratios, by the way, lie between 1:1 and 1:100, the average plasma power typically being 100 watt to 1000 watt. The amplitude of the individual high frequency power pulses effectively lies between 500 watt and 20,000 watt, preferably at ca 10,000 watt.

In continuation of the fourth exemplary embodiment, a fifth exemplary embodiment additionally provides that first, as already explained above, a pulsed inductively coupled plasma 14 is generated in an ICP source 13, using magnetic field support. In this connection, the magnetic field generated by magnetic field coil 21, which was always held constant at least to a great extent with respect to time, in the preceding exemplary embodiments, is now also pulsed.

Especially preferably, this pulsing of the magnetic field, which is brought about in a simple manner by corresponding current pulses generated by current supply unit 23, takes place in such a way that the magnetic field is only generated if simultaneously also a high frequency oscillation packet or a high frequency power pulse for generating or coupling in plasma power into inductively coupled plasma 14 is present at ICP source 13. As long as no plasma power is coupled in or no plasma is excited, as a rule no magnetic field support is

required either.

A possible and preferable synchronization in time of high frequency power pulses for coupling in plasma power in plasma 14 and current pulses through magnetic field coil 21 is explained, in this connection, with the aid of Figure 4.

Here, the coil current is switched on by magnetic field coil 21 in each case shortly before the application of a high frequency oscillation packet, i.e. a high frequency power pulse, and is switched off again after the end of this pulse.

Synchronization of current and high frequency power pulses can be ensured in a simple way, in this connection, by an impulse generator known per se, integrated into current supply unit 23, for example, which is furnished with additional time elements, in order to connect to the supply the high frequency power pulse with a certain delay of, for example, 10% of the set high frequency impulse duration after switching on the current of magnetic field coil 21, or to switch this current off again with a certain delay of, for example, 10% of the set high frequency impulse duration after the end of the high frequency power impulse. Such synchronization circuits and corresponding time elements for generating the needed time delays are in the related art and are generally known. For this, current supply unit 23 is further in connection with ICP coil generator 17.

Synchronization of the pulsing of magnetic field and coupled-in plasma power has the great advantage that thereby the ohmic heat losses arising in magnetic field coil 21 can be clearly reduced. Thereby the problems of cooling and temperature control are deactivated.

If, for example, the coupled-in plasma power is operated with a pulse/pause ratio of 1:20, the current can also be pulsed by the magnetic field coil at, for example, a pulse/pause ratio

of 1:18. In this connection, the duration of a current impulse by magnetic field coil 21 is always a little longer than the duration of a high frequency power pulse.

- 5 By this procedure, heat removal of magnetic field coil 21 is reduced to 1/18 of the original value. At the same time, use of electrical energy is reduced correspondingly.

10 Typical rates of repetition or pulse rates are oriented to the inductance of magnetic field coil 21, which limits the speed of change of the coil current. A rate of repetition of a few 10 Hz to 10 kHz is realistic for most magnetic field coils 21, depending on their geometry. Typical pulse/pause ratios for the high frequency power pulses lie between 1:1 and 1:100.

15 In this connection it is further very advantageous to apply the aperture, known from DE 197 34 278 and already explained, below magnetic field coil 21, a few cm above substrate 10 or substrate electrode 11, which carries substrate 10.

20 The use of this aperture improves, on the one hand, uniformity of the etching over the substrate surface, especially clearly with a symmetrically supplied ICP source 13. At the same time, the time-variable magnetic field - the transients - is also reduced at the location of substrate 10. In this connection, eddy currents in the aperture ring of the aperture lead to a dumping of the time-variable magnetic field components directly before substrate 10, so that induction processes on substrate 10 itself are weakened.

30 Such changing magnetic fields, so-called transients, could induce voltages in antenna structures on the substrate, which on their part could again lead to damage to the substrate, if the latter, for example, has integrated circuits or especially field effect transistors.

35

As for the rest, it should be emphasized that it is further

advantageous also to pulse the high frequency power, present  
at substrate 10 via substrate electrode 11, which is generated  
by substrate voltage generator 12 for the acceleration of the  
ions. This pulsing is then preferably also done correlated in  
5 time, or synchronized, with the pulsing of the magnetic field  
and/or the pulsing of the coupled-in plasma power.

## List of Reference Numerals

	1	frequency-selective component
	1'	filter characteristic line
5	1''	steady-state frequency
	2	matching network
	3	power element
	4	quartz oscillator
	5	plasma etching equipment
10	6	quartz-crystal oscillator
	7	delay line
	8	line
	9	generator control input
	9'	generator status output
15		
	10	substrate
	11	substrate electrode
	12	substrate voltage generator
	13	ICP source
20	14	inductively coupled plasma
	15	reactor
	16	first impedance transformer
	17	ICP coil generator
	18	second impedance transformer
25	19	gas supply
	20	gas exhaust
	21	magnetic field coil
	22	spacer
30	23	current supply unit
	24	decoupling capacitor
	25	signal tap
	26	center tap

35

What is claimed is:

1. A device for etching a substrate (10), particularly a silicon element, with the aid of an inductively coupled plasma (14), having an ICP source (13) for generating a high frequency electromagnetic alternating field and having a reactor (15) for producing the inductively coupled plasma (14) from reactive particles by the action of the high frequency electromagnetic alternating field upon a reactive gas, wherein a first means is provided which produces a static or timewise varying magnetic field between the substrate (10) and the ICP source (13).
2. The device as recited in Claim 1, wherein the first means surrounds the reactor (15) at least in some regions between the ICP source (13) and the substrate (10), in this region the wall of the reactor (15) being formed by a spacer (22).
3. The device as recited in Claim 1 or 2, wherein the first means is a magnetic field coil (21) having an appertaining current supply unit (23) or is a permanent magnet.
4. The device as recited in Claim 3, wherein the magnetic field produced by the magnetic field coil (21) is variable timewise, especially pulsable, with the current supply unit (23).
5. The device as recited in Claim 1, wherein the substrate (10) is positioned on a substrate electrode (11), and via the latter is able to be acted upon by a substrate voltage generator (12) with a continuous or timewise varying, especially a pulsed high frequency power.

6. The device as recited in Claim 1,  
wherein the reactor (15) on its inside has an aperture  
concentric with the reactor wall, positioned between the  
first means for producing the magnetic field and the  
substrate (10).
7. The device as recited in at least one of the preceding  
claims,  
wherein a second means is provided with which a plasma  
power coupled by the ICP source (13) into the inductively  
coupled plasma (14) via the high frequency  
electromagnetic alternating field, can be set.
8. The device as recited in Claim 7,  
wherein the second means is an ICP coil generator (17)  
which produces a variably adjustable high frequency  
power, particularly periodically varying or pulsed, which  
can be coupled as plasma power into the plasma (14).
9. The device as recited in Claim 8,  
wherein, using the ICP coil generator (17), an average  
plasma power of 300 watt to 5000 watt can be coupled into  
the inductively coupled plasma (14).
10. The device as recited in Claim 7,  
wherein a second impedance transformer (18) is provided  
in the form of an especially balanced symmetrical  
matching network for matching an output impedance of the  
ICP coil generator (17) to a plasma impedance which is a  
function of the coupled-in plasma power.
11. The device as recited in Claim 10,  
wherein the second impedance transformer (18) is preset  
in such a way that an at least largely optimal impedance  
matching is ensured, in response to a predefined maximum  
plasma power to be coupled into the inductively coupled  
plasma (14).

12. The device as recited in Claim 8,  
wherein components are integrated into the ICP coil generator (17) which carry out a variation of the frequency of the generated electromagnetic alternating field, for matching the impedance as a function of the plasma power to be coupled in.
13. The device as recited in Claim 12,  
wherein, for varying the frequency, the ICP coil generator (17) is provided with an automatically acting feedback circuit having a frequency-selected component (1).
14. The device as recited in at least one of Claims 8 through 13,  
wherein the ICP coil generator (17) is furnished with at least one regulated power element, one frequency-selective band-pass filter having a steady-state frequency (1") to be reached, and a delay line (7) or a phase shifter.
15. The device as recited in at least one of the preceding claims,  
wherein the IC coil generator (17) is in connection with the current supply unit (23) and/or the substrate voltage generator (12).
16. A method for etching a substrate (10), especially a silicon element, using a device as recited in at least one of the preceding claims,  
wherein, during the etching, a static or timewise varying, particularly a periodically varying or pulsed magnetic field is produced, whose direction is at least approximately or predominantly parallel to the direction defined by the connecting line of the substrate (10) and the inductively coupled plasma (14).



17. The method as recited in Claim 16,  
wherein the magnetic field is produced in such a way that  
it extends into the region of the substrate (10) and the  
inductively coupled plasma (14).
18. The method as recited in Claim 16,  
wherein the magnetic field is produced using an amplitude  
of the field strength, on the inside of the reactor (15),  
between 10 mTesla and 100 mTesla.
19. The method as recited in Claim 16,  
wherein the inductively coupled plasma (14) is produced  
with a high frequency electromagnetic alternating field  
having a constant frequency, or with a frequency varying,  
within a frequency range, about a steady-state frequency  
(1'), especially 13.56 MHz.
20. The method as recited in Claim 16,  
wherein the etching takes place in alternating etching  
and passivating steps.
21. The method as recited in Claim 16,  
wherein the etching takes place at a process pressure of  
5  $\mu$ bar to 100  $\mu$ bar and a coupled-in average plasma power  
of 300 watt to 5000 watt.
22. The method as recited in Claim 16,  
wherein a pulsed magnetic field is produced, via a  
current supply unit (23), whose amplitude of the field  
strength, on the inside of the reactor (15), lies between  
10 mTesla and 100 mTesla.
23. The method as recited in Claim 22,  
wherein the magnetic field is pulsed at a frequency of 10  
Hz to 20 kHz, and a pulse/pause ratio of 1:1 to 1:100 is  
set.

24. The method as recited in at least one of the preceding claims,  
wherein a variably adjustable, particularly periodically varying or pulsed high frequency power is produced and is coupled as plasma power into the inductively coupled plasma (14).
25. The method as recited in Claim 24,  
wherein an ICP coil generator (17) having a frequency of 10 Hz to 1 MHz is operated in pulsed fashion for producing the plasma power, and an average plasma power of 300 watt to 5000 watt is thereby coupled into the inductively coupled plasma (14).
26. The method as recited in Claim 25,  
wherein the ICP coil generator (17) is operated using a pulse/pause ratio of 1:1 to 1:100.
27. The method as recited in Claim 24,  
wherein the pulsing of the coupled-in plasma power is accompanied by a change in the frequency of the coupled-in high frequency power.
28. The method as recited in Claim 27,  
wherein the frequency change is controlled in such a way that the plasma power coupled into the inductively coupled plasma (14) during the pulsing is maximum.
29. The method as recited in Claim 27,  
wherein the ICP coil generator (17) is operated in the form of an automatically acting feedback circuit, and the frequency of the high frequency power produced, which forms the coupled-in high frequency electromagnetic alternating field, is varied about the steady-state frequency (1'').
30. The method as recited in at least one of the preceding

claims, wherein the pulsing of the magnetic field correlates in time or is synchronized with the pulsing of the coupled-in plasma power and/or the pulsing of the high frequency power coupled into the substrate (10) via the substrate voltage generator (12).

31. The method as recited in Claim 29,  
wherein the synchronization takes place in such a way that the magnetic field is first applied before a high frequency power pulse of the ICP coil generator (30) for the coupling of the plasma power into the inductively coupled plasma (14), and the magnetic field is only switched off again after the high frequency power pulse has faded out.
32. The method as recited in Claim 30,  
wherein the pulse/pause ratio of the magnetic field pulses is greater than the pulse/pause ratio of the high frequency power pulses, and the magnetic field is held at least approximately constant during the high frequency power pulses.

## Abstract

A method and a suitable device for carrying out this method is proposed, for etching a substrate (10), especially a silicon element, with the aid of an inductively coupled plasma (14). For this purpose, a high frequency electromagnetic alternating field is generated, which produces an inductively coupled plasma (14) from reactive particles in a reactor (15). In this connection, the inductively coupled plasma (14) comes about by the action of the high frequency electromagnetic alternating field upon a reactive gas. Furthermore, a device, in particular a magnetic field coil (21) is provided which produces a static or timewise varying magnetic field between the substrate (10) and the ICP source (13). For this, the magnetic field is oriented in such a way that its direction is at least approximately or predominantly parallel to the direction defined by the line connecting the substrate (10) and the inductively coupled plasma (14).

Figure 1

DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING  
AN INDUCTIVELY COUPLED PLASMA

FIELD OF THE INVENTION

The present invention relates to a device and a method for etching a substrate, for example, a silicon element, by using an inductively coupled plasma.

BACKGROUND INFORMATION

In order to implement an anisotropic high rate etching method, for example, for silicon, using an inductive plasma source, it is necessary in one method, described, for example, in German Published Patent Application No. 42 41 045, to perform efficient sidewall passivation in as short a time as possible, during so-called passivating steps, and furthermore to achieve as high a concentration as possible of silicon-etching fluorine radicals during so-called etching steps. In order to achieve an etching rate that is as high as possible, it is conventional to work with as high as possible a high-frequency power at the inductive plasma source, and thereby to couple in as high as possible plasma powers into the generated inductively coupled plasma.

However, there are limits to these high-frequency powers, which result, on the one hand, from load capacity of the electrical components of the plasma source, but, on the other hand, are also of a process technology nature. Thus, high-frequency powers of an inductive plasma source reinforce harmful electrical intervention by the source region in the inductively coupled plasma generated, which deteriorate the etching results on the substrate wafer.

Also, in etching processes according to the kind described in German Published Patent Application No. 42 41 045, stability problems appear in the coupling in of the plasma in the

changeover phases between etching and passivating steps. This is based on the fact that, in response to high power to be coupled in, in the kwatt range, power reflection and overvoltage appearing during the changeover phases can have a destructive effect on the electrical circuit of the plasma source (coil, connected capacitors, generator output stage).

On this point, German Published Patent Application No. 199 00 179 describes an inductive plasma source, further refined compared to the one described in German Published Patent Application No. 42 41 045, which, with the aid of a loss-free symmetrical high-frequency supply of the coil of the inductive plasma source, is suitable for especially high plasma powers, and generates an inductive plasma which is particularly poor in electrical interference induced voltages. But for this source type, there exists a practicable power limit of about 3 kwatt to 5 kwatt, above which the required high-frequency components become extremely expensive, or, with respect to plasma stability, problems take the upper hand.

A possible approach towards attaining higher etching rates within a manageable power scope is to raise the efficiency of the plasma generation. In this connection, using magnetic fields to raise plasma efficiency is conventional.

By applying a magnetic field to a plasma, as is conventional, the electron paths in the plasma are bent, and because of that the residence time of the electrons in the plasma is increased, i.e. the time until they reach a wall which absorbs the electrons, so that each electron can interact more often with surrounding gas atoms until it leaves the effective plasma excitation region. Such impact interactions between electrons and gas molecules lead to the desired ionization or dissociation of the gas molecules along with the release of radicals needed for the etching process.

According to the related art, a so-called "multipole confinement" includes a metallic, nonferromagnetic wall having a plurality of permanent magnets of alternating polarity, which reflects electrons from the wall outfitted with these magnets by the action of magnetic fields. Thereby, a higher electron density can be generated within this "multipole confinement". An analogous RIE (reactive ion etching) source is marketed, for example, by TEGAL Corporation, Petaluma CA 94955-6020, USA, as a so-called "HRe<sup>-</sup> Source".

Other conventional plasma source types further make use of a magnetic field having a field direction parallel to a substrate electrode. Thus, by using a kind of Helmholtz coil pair directly at the substrate electrode, a field distribution is generated that is as homogeneous as possible, which leads to increased length of the electron paths, and thereby to the generation of greater plasma densities. For the further homogenization of the effects, this horizontally oriented magnetic field as, for example, in the MRIE (magnetically enhanced reactive ion etching) equipment of Allied Materials, Inc., Santa Clara CA 95054-3299, USA, can further be rotated slowly in a planar manner.

In the case of so-called ECR (electron cyclotron resonance) sources, it is conventional that one should tune a longitudinal magnetic field in such a way that the circulation frequency of the electrons in this magnetic field, the so-called cyclotron frequency, is resonant with the frequency of the coupled-in microwave radiation, at least in a certain volume range of the etching reactor. Thus, an especially efficient plasma excitation by microwave irradiation can occur at a sufficiently free path length of the electrons, which opens up to such ECR sources the low-pressure range of process pressures lower than 1  $\mu$ bar as a field of application. In this connection, the low pressure is a necessary condition for a sufficiently great path length of the electrons and for efficient plasma excitation. At higher pressures, ECR sources

rapidly become inefficient, and go over to an unwanted thermal plasma generation. The advantage of the magnetic inclusion and the resonant excitation are thereby lost to a considerable extent.

5

It follows from the formula for the cyclotron frequency  $\omega = eB/m$  that  $B = m\omega/e$ , i.e., at the usually irradiated microwave frequency of 2.45 GHz the magnetic field strength required for cyclotron resonance is 87.6 mTesla.

10

This application is not simply transferable to the case of high-frequency excitation in the MHz range, i.e., the case of typical frequencies for ICP (inductively coupled plasma) sources, since the free path lengths of the electrons, required for this, assume extremely low, impracticable pressures. After all, an inductive plasma source for high rate etching methods has to be configured for a relatively high pressure range of approximately 30 to 100  $\mu$ bar.

15

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The usual high frequency of 13.56 MHz, used for inductive plasma excitation using ICP sources, would further, in the case of cyclotron resonance, imply a resonance field strength of only 0.5 mT. However, such a low field hardly has any remaining guidance function for the electrons. For a sufficient guidance function, i.e., suppression of wall losses of the electrons in an extended plasma volume, field strengths of 10 mTesla or rather several times 10 mTesla to 100 mTesla are required.

25

Magnetic coils in an ECR-type configuration are also usually placed above, or at the same height as the plasma source, so as to generate the greatest field strength directly at the location of plasma generation, and so as to have the greatest possible influence on the plasma generating mechanism there.

30

In the direction of the substrate to be etched, then, the magnetic field strength decreases rapidly because of the divergence of the magnetic field, so that the guidance



function of the magnetic field is no longer sufficiently present in such an arrangement.

Varying plasma power coupled in an inductively coupled plasma having a high-frequency electromagnetic alternating field, adiabatically, between individual method steps, especially alternating etching and passivating steps, is described in German Published Patent Application No. 199 19 832. Such an adiabatic power transition, i.e., a gradual running-up or lowering of the coupled-in plasma power along with simultaneous continuous matching of the impedance of the ICP source to the respective plasma impedance as a function of the coupled-in plasma power, with the aid of an automatic matching network or an impedance transformer ("matchbox"), makes it possible to control the explained problems with regard to power reflection and voltage magnification in response to switching on and off plasma powers in the range of 1 kwatt to 5 kwatt. However, in this connection, a typical duration of transient effects is in the range of 0.1 sec to 2 sec. Therefore, power changes cannot be made by this approach.

#### SUMMARY

Compared to the related art, the device according to the present invention has the advantage that it makes available a plasma etching equipment having inductive plasma generation or a plasma inductively coupled via an ICP source, in which an additional constant magnetic field, or one varying with time, considerably increases the efficiency of plasma generation. In this connection, the inductively coupled plasma generated, starting from the plasma source, is guided through the generated magnetic field in a kind of magnetic bottle to a substrate to be etched. For this purpose, a magnetic field coil or a sufficiently strong permanent magnet having longitudinal field direction is placed between the inductive plasma source (ICP source) and the substrate or a substrate electrode carrying the substrate, such as a silicon wafer.

Thus, when performing the method according to the present invention, this device effects a very efficient plasma generation in the area of inductive excitation, and a low-loss plasma transport right up to the substrate to be etched. At the same time, decoupling of plasma generation and the generation of the magnetic field is achieved. Because of the symmetry of the configuration of the device according to the present invention, despite the nonhomogeneous field distribution of the magnetic coil, good uniformity on the substrate surface may be maintained.

Thus, by using the generated longitudinal magnetic field, i.e., a magnetic field the direction of which is at least approximately or predominantly parallel to the direction defined by the connecting line from the substrate to the inductively coupled plasma, the high-frequency power at the ICP source, required for high rate etching at the highest etching rates, is thus reduced by efficient utilization of the coupled-in high-frequency power for generating the desired plasma species (electrons, ions, free radicals). Because of this, higher etching rates are possible at equal plasma power.

Because the generation of the longitudinal magnetic field is placed between the ICP source and the substrate, both the substrate and the area of plasma generation in the reactor are arranged in a region of relatively high magnetic field strengths, and, thus, of good guidance of the electrons and ultimately also the ions.

In addition, electrical interference effects from the source region may be effectively reduced by the improvement, achieved with the device according to the present invention, of the economics of the ICP source and the possibility, that goes with it, of reducing power without reducing the etching rate, or with an etching rate increase at equal plasma power. Therefore, the etching result is achieved more economically.

Furthermore, a power that is constant, pulsed or generally varying with time may be made available considerably more cost-effectively than a greater high-frequency power for coupling in the plasma. This power demonstrates no harmful effect on the etching process or components of the plasma etching equipment.

Thus, the device according to the present invention may include an aperture positioned concentrically with the inner wall of the reactor, which may be arranged approximately 5 cm above the substrate positioned on a substrate electrode. Such an aperture construction is described, for example in German Published Patent Application No. 197 34 278.

The plasma etching equipment according to the present invention may also be furnished with a balanced, symmetrically configured and symmetrically supplied configuration of the ICP source, as described in German Published Patent Application No. 199 00 179.

A magnetic field coil having an appertaining current supply unit may be suitable for generating the magnetic field, since with that, the generated magnetic field is timely, and, with regard to its strength, is variable and, in particular, pulsable.

An ICP coil generator may be provided, which generates a variably adjustable, especially periodically varying or pulsed high-frequency power, which may be coupled into the inductively coupled plasma as plasma power.

Components may be integrated into the ICP coil generator which perform a variation of the frequency of the generated electromagnetic alternating field, for adapting the impedance as a function of the plasma power to be coupled in. An automatically acting feedback circuit having a frequency-

selective component along the lines of a Meissner oscillator may be suitable for this.

The pulsing of the generated magnetic field may be correlated in time or synchronized with the pulsing of the coupled-in plasma power and/or the pulsing of the high-frequency power coupled into the substrate via the substrate voltage generator.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic view of a plasma etching equipment.

Figure 2 is a schematic view of an electronic feedback circuit having a connected ICP source.

Figure 3 illustrates an example of a filter characteristic curve.

Figure 4 illustrates an example of a correlation in time of high-frequency power pulses and magnetic field pulses.

#### DETAILED DESCRIPTION

Figure 1 illustrates a first example embodiment of the present invention. A plasma etching equipment 5 includes a reactor 15, in the upper region of which an inductively coupled plasma 14 is generated in a conventional manner via an ICP (inductively coupled plasma) source 13. The following are also provided here: a gas feed 19 for supplying a reactive gas such as  $\text{SF}_6$ ,  $\text{ClF}_3$ ,  $\text{O}_2$ ,  $\text{C}_4\text{F}_8$ ,  $\text{C}_3\text{F}_6$ ,  $\text{SiF}_4$  or  $\text{NF}_3$ , a gas discharge 20 for removing reaction products, a substrate 10 such as a silicon body or a silicon wafer to be structured by the etching method according to the present invention, a substrate electrode 11 which is in contact with substrate 10, a substrate voltage generator 12, and a first impedance transformer 16. Substrate voltage generator 12 also couples in a high-frequency alternating voltage or high-frequency power into substrate electrode 11 and above that into

substrate 10, causing acceleration of ions generated in inductively coupled plasma 14 onto substrate 10. The high-frequency power or alternating voltage input in this manner is typically between 3 watts and 50 watts and 5 volts and 100  
5 volts in continuous operation and in pulsed operation respectively, each averaged over time over the pulse sequence.

In addition, an ICP coil generator 17 is also provided, which is connected to a second impedance transformer 18, and above  
10 that with ICP source 13. Thus, ICP source 13 generates a high-frequency electromagnetic alternating field and also an inductively coupled plasma 14 composed of reactive particles and electrically charged particles (ions) formed by the action of the high-frequency electromagnetic alternating field on the  
15 reactive gas in reactor 15. ICP source 13 includes a coil for this having at least one winding.

Second impedance transformer 18 may be configured in the manner described in German Published Patent Application No.  
20 199 00 179, so that a balanced symmetrical arranged configuration and supply of ICP source 13 over ICP coil generator 17 are obtained. This guarantees that the high-frequency alternating voltages applied to the two ends of the coil of ICP source 13 are at least approximately in phase  
25 opposition to each other. Furthermore, the center tap of the coil of the ICP source may be grounded, as illustrated in Figure 2.

The anisotropic high-rate etching process for silicon, having  
30 alternating etching and passivating steps, described in German Published Patent Application No. 42 41 045, is further performed, for example, using plasma etching equipment 5. With respect to further details, known to one skilled in the art, concerning plasma etching equipment 5, as described up to  
35 this point as being known from the related art, and the etching method performed with it, especially with respect to the reactive gases, the process pressures and the substrate

electrode voltages in each respective etching step or passivating step, as the case may be, reference may be made to German Published Patent Application No. 42 41 045.

- 5 Plasma etching equipment 5 is also suitable for supervisory control, as described in German Published Patent Application No. 199 27 806.

10 During the etching of substrate 10, for example, during the passivating steps in reactor 15, passivating is performed, for example, at a process pressure of 5  $\mu$ bar to 20  $\mu$ bar, and a plasma power, coupled into plasma 14 via ICP source 13, of 300 to 1000 Watt.  $C_4F_8$  or  $C_3F_6$ , for example, are suitable as passivating gases. During the subsequent etching steps, 15 etching is performed, for example, at a process pressure of 30  $\mu$ bar to 50  $\mu$ bar and a high plasma power of 1000 to 5000 Watt.  $SF_6$  or  $ClF_3$ , for example, are suitable as reactive gas.

20 An example embodiment of the plasma etching equipment further provides that, to improve the selectivity of an etching base polymer removal relative to the sidewall film removal, the ion acceleration voltage applied to the substrate by substrate voltage generator 12 be switched back by reduction of the coupled-in plasma power in the etching steps, each time after 25 breakthrough of the initial etching base polymer, as described in German Published Patent Application No. 199 19 832 and explained in detail.

30 This switching back here occurs in a conventional manner, either abruptly or continuously via a time-related ramp function. This achieves a further improvement of the silicon etching rate, of the selectivity of the etching process with respect to a masking material, of the profile accuracy and, for example, of the suppression of pockets in a dielectric 35 etch-stop layer.

In addition, according to the present invention, a so-called "spacer" is further placed as spacer 22, made of a nonferromagnetic material such as aluminum, between inductively coupled plasma 14 or ICP source 13, i.e., the actual plasma excitation zone, and substrate 10. This spacer 22 is concentrically set into the wall of reactor 15 as a spacer ring, and thus forms the reactor wall, from place to place. It includes a typical height of approximately 5 mm to 30 mm at a typical diameter of reactor 15 of 30 to 100 cm.

Spacer 22 further surrounds a magnetic field coil 21, which has, for instance, 100 to 300 turns and is wound with a lacquered copper wire of a sufficient gauge for the strength of current to be used. Additionally, copper pipes may be accommodated in magnetic field coil 21, having cooling water flowing through them so as to remove heat losses from magnetic field coil 21.

Alternatively, it is also possible to wind magnetic field coil 21 itself from a thin copper pipe lacquered with an electrically insulating material, and having the cooling water flowing through it directly.

An electric current such as 10 to 100 amp is conducted through magnetic field coil 21 via a current supply unit 23.

In the example embodiment, this is, for example, a d.c. current which generates a static magnetic field on the inside of reactor 15, which, in the case of a magnetic field coil 21 having 100 turns and a length of 11 cm as well as a diameter of 40 cm generates a magnetic field strength in the center of magnetic field coil 21 of about 0.3 mTesla/A of current flow.

For a significant increase of plasma generating efficiency and sufficient magnetic guidance of inductively coupled plasma 14, 10 mT to 100 mT, for example 30 mT, are required, as explained above. That means, current supply unit 23 makes available

current strengths of about 30 to 100 amp during etching of a substrate 10, using plasma etching equipment 5.

5 Instead of magnetic field coil 21, a permanent magnet may be used. Such a permanent magnet may require no energy, but may have the disadvantage that setting the magnetic field strength, which is of advantage for setting an optimum etching process, is not possible. Furthermore, the field strength of a permanent magnet is temperature dependent, so that magnetic  
10 field coil 21 may be preferred.

It is important in each case that the direction of the magnetic field generated by magnetic field coil 21 or by the permanent magnet is at least approximately or predominantly  
15 parallel to the direction defined by the connecting line of substrate 10 and inductively coupled plasma 14 or the plasma generating zone (longitudinal magnetic field orientation).

A refinement of the explained example embodiment further  
20 provides for installing an aperture described in German Published Patent Application No. 197 34 278, for improvement of the uniformity of the etching process. For reasons of clarity, this aperture is omitted in Figure 1. It is mounted on the inside of reactor 15, concentrically with the reactor  
25 wall, between ICP source 13 or the plasma excitation zone and substrate 10. It may be fastened on spacer 22, approximately 5 cm above substrate electrode 11 or substrate 10.

Also, in case of the use of a magnetic field coil 21, a  
30 suitable monitoring device may be integrated into current supply unit 23, the monitoring device being integrated into the process sequence control, and performing a monitoring of the coil temperature and emergency switching-off, for example, when there is a shortage of cooling water.

35 In the first example embodiment, during etching, ICP coil generator 17 couples continuously during the etching steps or



passivating steps an at least to a great extent constant plasma power of a minimum of 300 Watt to a maximum of 5000 Watt into inductively coupled plasma 14.

5 During the passivating steps, a plasma power of 500 Watt, for example, is coupled into inductively coupled plasma 14, and during the etching steps a plasma power of 2000 Watt, for example, is coupled into inductively coupled plasma 14. ICP coil generator and second impedance transformer 18, in the  
10 manner described in German Published 199 19 832 and explained above, in response to a transition from a passivating to an etching step, performing an adiabatic up-regulating of the coupled-in plasma power over a time-related ramp function and, at the same time, via second impedance transformer 18,  
15 performing an automatic, stepwise or continuous impedance adaptation.

A second example embodiment of the present invention provides that, as a modification of the first example embodiment,  
20 instead of adiabatic control of the high-frequency power coupled into the inductively coupled plasma 14 by IPC source 13, and instead of a matching of the coupled-in high-frequency power given at any point in time, via the automatic matching network ("matchbox") as the second impedance transformer 18,  
25 to the plasma impedance changing with increasing plasma power, alternatively the previously constant frequency of the high-frequency electromagnetic alternating field, which ICP coil generator 17 produces, may be varied for impedance matching.

30 The matchbox, which may be symmetrically configured and may supply ICP source 13 symmetrically in second impedance transformer 18 may be, in this connection, set in such a way that it ensures an optimum impedance matching in the steady-state power case. This steady-state power case is  
35 characterized in that, in this connection, the plasma power inductively coupled into plasma 14 has reached a high maximum or final value such as 3000 watt to 5000 watt, a steady-state

frequency or a resonant frequency 1'' of, for example, 13.56 MHz of the frequency produced by ICP coil generator 17 of the high-frequency electromagnetic alternating field having simultaneously been reached.

5

The steady-state frequency 1' of conventional ICP coil generators 17 is generally 13.56 MHz, besides this standard, generators having other frequencies or frequency ranges may also be commercially obtainable. However, in such ICP coil generators 17, in deviation from the realization according to the present invention, the steady-state frequency 1'' is set to a fixed value which is, for example, derived with great accuracy from the natural frequency of a quartz-crystal oscillator. Thus, during a power change, for example, during the run-up of the plasma power to be coupled into plasma 14 from, for instance 500 watt to 3000 watt at a steady frequency of the high-frequency of high-frequency alternating field generated by ICP coil generator 17, with a predefined setting of impedance transformer 18, no matching, or only a poor one, to the plasma impedance changing as a function of the plasma power is possible, so that high reflected powers appear during the transients. However, if the frequency of ICP coil generator 17 is enabled in such phases, then by a change in the frequency of the high-frequency electromagnetic alternating field, a substantially optimum impedance adaptation, even under quickly changing plasma conditions, may be maintained.

An advantage of the production of the correct impedance matching via a variable frequency of the high-frequency power of coil generator 17 is that this frequency change may be performed very fast because it is limited only by the control rate of the corresponding electronic circuit. That makes possible reaction times in the microsecond range, without any problem.

In contrast, manual or automatic setting of an matching network requires the change of mechanical quantities in second impedance transformer 18, for example, the resetting of variable capacitors by motors, which occurs correspondingly slowly. Typical time constants here lie in the range of tenths of seconds.

According to the second example embodiment, a control circuit integrated in second impedance transformer 18, for example, in a conventional manner, detects the instantaneous control error, i.e., the faulty adaptation of the impedance of the output of ICP coil generator 17 and the impedance of ICP source 13, with respect to amplitude and phase. This may occur by a measurement of the signal reflected at ICP source 13 or second impedance transformer 18, using reflectometers sufficiently conventional in high-frequency technology, amplitude and phase errors being detected.

From this information, a corresponding frequency change of the electromagnetic alternating field at ICP coil generator 17, required in each case, is ascertained, for example, continuously within a predefined frequency range, so that the control errors with respect to amplitude and phase may be minimized. This basically only corrects an amplitude error, since, as is conventional, to a great extent only the real plasma resistance changes as a function of the coupled in plasma power, and the phase relationship of the impedances is set correctly, at least roughly, just by the explained presetting of second impedance transformer 18.

When the output power of ICP coil generator 17, and with that also the plasma impedance finally become steady-state after completion of the run-up of the plasma power, the control circuit takes the frequency of ICP coil generator 17, or of the electromagnetic alternating field generated, back to the actually desired fixed value such as 13.56 MHz, and fixes it there. In this connection, for the frequency in the case of

the steady-state power, second impedance transformer 18 is set correctly via the presetting ascertained before, which is a function of the maximum plasma power to be reached, and this can may be done either manually or automatically, using low-speed control characteristics.

To sum up, if the frequency of ICP coil generator 17 is thus fixed, in the steady-state case of the power to be coupled in, at, for example, 13.56 MHz, whereas, during the course of the unstable run-up phases of the generator output power, the frequency is temporarily released within a certain bandwidth, and is controlled by an electronic control system for impedance matching. Thus, it is possible to perform even very fast power changes of the generator output power in the range of microseconds in a stable manner, at simultaneous high power changes, which is not possible using known matching networks or impedance transformers.

This is explained, for example, with the aid of Figure 3, in which a filter characteristic line 1' is illustrated, which illustrates a preset frequency range within which the frequency of ICP coil generator 17 may be varied, each frequency being assigned a certain high-frequency power or plasma power to be coupled in, or a coupling loss A of the power of ICP coil generator 17. The frequency to be reached in the case of steady-state power, in this connection, is the steady-state frequency 1'', which may be 13.56 MHz, for example, and at which the predefined maximum power is supplied as the plasma power to inductively coupled plasma 14.

A third example embodiment of the present invention, in continuation of the second example embodiment explained above, further provides leaving the frequency variation of ICP coil generator 17 to an automatically acting feedback circuit, so that one may do without measuring the faulty adaptation in each case or measuring the reflected signals, for example, by

reflectometer. This is explained in more detail with the aid of Figure 2.

5 In this connection, ICP source 13, i.e., its coil, to be exact, in a conventional manner as described in German Published Patent Application No. 199 00 179, is first energized by a, for example, balanced symmetrical matching network 2 from an unbalanced unsymmetrical output of ICP coil generator 17. Adaptation network 2 is a part of second  
10 impedance transformer 18.

The ICP coil generator 17 is further, in this case, made similar to a widespread specific embodiment, including a high-frequency power element 3 and a quartz oscillator 4 for  
15 producing a high-frequency fundamental wave having a fixed frequency such as 13.56 MHz.

Conventionally, the high-frequency fundamental wave of quartz oscillator 4 is normally supplied to the amplifying input of  
20 power element 3. According to the present invention, however, this supply is modified in such a way that quartz oscillator 4 is made accessible separately from the amplifier input of power element 3, and its input is made accessible externally, for example, via a corresponding input socket. Since the  
25 quartz oscillator in this specific embodiment no longer provides a function, it may be suitably deactivated.

Power element 3 further includes generator control inputs 9 in a convention manner, which are used for external control of  
30 ICP coil generator 17. Using them makes possible, for example, switching on and off ICP coil generator 17 or the stipulation of a high-frequency power to be generated. In addition, generator status outputs 9' are possible, for the feedback of generator data such as, for instance, generator  
35 status current output power, reflected power, overload, etc., to an external control unit (machine control), or to current supply unit 23 of plasma etching equipment 5.

The amplifier input of power element 3 is suitably connected to ICP source 13, in the sense of a feedback circuit via a frequency-selective component 1.

5 In this connection, additionally, capacitors, inductance coils and resistors or combinations of these may be interconnected and provided in a conventional manner as voltage dividers, in order to weaken the high voltages that appear at the coil of ICP source 13 to a suitable measure for frequency-selective  
10 component 1 or the amplifier input of power element 3. Such voltage dividers are conventional, and are indicated in Figure 2 only by a decoupling capacitor 24 between the coil of ICP source 13 and frequency-selective component 1. Alternatively, one may also move signal tap 25 to the vicinity of the drawn-  
15 in grounded center point or center tap 26 of the coil of ICP source 13, where correspondingly lower voltage levels are present. Depending on the distance of the signal tap, which, for example, may be configured as an adjustable clip contact, from grounded center tap 26 of the coil of ICP source 13, a  
20 larger or smaller tapped voltage may be set, and thus favorable level ratios may be achieved.

Frequency-selective component 1 is represented in the example as a tunable arrangement of coils and capacitors, so-called LC  
25 resonant circuits, which together form a band-pass filter. This band-pass filter includes as conducting state region a certain predefined bandwidth such as 0.1 MHz to 4 MHz, and a filter characteristic line 1', as illustrated as an example in Figure 3.

30 The band-pass filter has a resonance or steady-state frequency 1'' having maximum signal transmission. This steady-state frequency 1'' may be 13.56 MHz, for example, and may be fixed exactly, for example, by a quartz-crystal oscillator 6 or a  
35 piezoceramic filter element as additional components of the band-pass filter.

Alternatively, it is also possible, instead of LC resonant circuits, to combine so-called piezoceramic filter elements, or other conventional frequency-selective components into a band-pass filter having the desired filter characteristic line, bandwidth and steady-state frequency  $\omega'$ .

The arrangement described above controlled power element 3, matching network 2, ICP source 13 and band-pass filter represents in total a feedback circuit of the same kind as a Meissner oscillator.

During operation, this first begins to oscillate in the neighborhood of steady-state frequency  $\omega'$ , in order to build up to a predefined output power of power element 3. The phase relationship, required for the build-up, between generator output and signal tap 25 is set correctly for this purpose once, in advance, for example, via a delay line 7 of specific length, and with that, via the phase shift defined by the signal propagation time or a phase shifter instead of delay line 7. This ensures that the coil of ICP source 13 has damping reduced with a correct phase.

Via delay line 7 it is further ensured that, at the location of ICP source 13, the driving electrical voltage and the current in the coil of ICP source 13 have a resonance phase of approximately  $90^\circ$  to each other.

In practice, the resonance condition of the feedback circuit with regard to frequency-selective component 1 is not severe, so that, in general, a small frequency shift in the neighborhood of resonance or steady-state frequency  $\omega'$  is sufficient for almost automatically correcting the resonance condition with respect to the phase. Therefore, it is sufficient to correct the resonance condition only approximately by the outer circuit elements, so that the resonant circuit builds up somewhere close to its steady-state frequency  $\omega'$ .

However, if all phase shifts from signal tap 25 of the coil of ICP source 13 via the band-pass filter into the input of power element 3, and through the power element back to second impedance transformer 18 into the coil of ICP source 13 should sum up so unfavorably that actually dumping instead of damping reduction of the resonant circuit occurs, the system cannot begin to oscillate. The feedback then becomes an unwanted negative feedback instead of the desired positive feedback. The setting of this approximately correct phase is accomplished by delay line 7, the length of which should therefore be set at one time in such a way that the feedback acts constructively, i.e., to reduce damping.

Thus, in the case of faulty adaptation to the plasma impedance, for example, during rapid power changes, the explained feedback circuit may thus give way in its frequency within the band pass of the band-pass filter, and always maintain a largely optimum impedance matching, even during rapid impedance changes of inductively coupled plasma 14.

Then, as soon as inductively coupled plasma 14 stabilizes with regard to the plasma impedance or the coupled-in plasma power, the frequency of ICP coil generator 17 will return again to near or exactly the value of the maximum pass frequency, which is given by the resonant frequency or steady-state frequency  $f''$ . This matching of the impedance by frequency variation occurs automatically and very rapidly within a few periods of oscillation of the high-frequency voltage, i.e., in the microsecond range.

The connection between the output of power element 3 and the input of second impedance transformer 18 is made by line 8, which is configured as a coaxial cable, and is capable of carrying a power of a few kwatt.

With this automatically building-up arrangement, or even with the arrangement described above, having active frequency



control for matching to rapidly changing plasma impedances, it is also possible to perform a pulsed operation of the inductive plasma source.

5 In the case of the refinement of the ICP coil generator described in the fourth example embodiment, it is further possible to perform a pulsed operation of ICP source 13, and thereby, for example, also to couple in pulsing plasma power during the etching or passivating steps of the etching method.

10 To do this, the output power of ICP coil generator 17, for example, is periodically switched on and off using a repetition frequency of typically 10 Hz to 1 MHz, such as 10 kHz to 100 kHz, i.e., it is pulsed, or the envelope curve of  
15 the output voltage of ICP coil generator 17 has its amplitude modulated by a suitable modulating voltage. Such devices for amplitude modulation conventional from high-frequency technology.

20 For example, generator control input 9 may be used to select the setpoint value of the high-frequency power of ICP coil generator 17 for the purpose of supplying the signal modulating the high-frequency power of ICP coil generator 17.

25 Since, in response to a pulsed operation of ICP source 13, very rapid impedance changes appear in plasma 14, it is conventionally impossible, especially with power in the kwatt range, to avoid the occurrence of high reflected power during switching on and off coupled-in high-frequency power pulses,  
30 or at least to make these harmless.

In contrast, by using the device explained in this example embodiment, the impedance matching of inductively coupled plasma 14, or ICP source 13, and ICP coil generator 17 is  
35 ensured at all times, in this case as well.

Compared to a continuous operation, a pulsed operation of ICP source 13 has the further advantage that, during the high-frequency power pulses or during the plasma power pulses a substantially higher plasma density may be achieved than in continuous operation. This is based on the fact that generation of an inductive plasma is a high-grade nonlinear process, so that the average plasma density in this pulsed operational mode is higher than in the case of an average plasma power corresponding to the time average.

Therefore, in pulse operation one effectively obtains more reactive species and ions with respect to the time average than in continuous operation. This is true when so-called "giant impulses" are used, i.e., relatively brief and extremely high-powered high-frequency power impulses such as 20 kwatt peak power, as is possible with the device according to the present invention, the average plasma power at time average being, for example, only 500 watt.

In this connection, unavoidable heat losses in ICP coil generator 17 and other equipment components of plasma etching equipment 5 are correlated with the relatively low time-averaged value of the plasma power, whereas desired plasma effects, particularly the achievable etching rates, may correlate with the occurring peak powers. As a result, the efficiency of generation of reactive species and ions is improved.

In this connection, ICP coil generator 17 and the remaining components of plasma etching equipment 5 involved may be configured in such a way that they may process even the occurring peak loads (peak currents and peak voltages) without damage. On account of the high voltage peaks at the inductive coil, the balanced supply of the ICP coil may have an advantageous effect on obtaining favorable plasma properties.

A further advantage of pulsed operation of ICP source 13 is that interfering electrical charges on substrate 10 to be etched may be discharged during the pauses between the high-frequency power pulses, and profile control during etching may thereby be improved in toto.

Typical pulse/pause ratios are between 1:1 and 1:100, the average plasma power typically being 100 watt to 1000 watt. The amplitude of the individual high-frequency power pulses effectively is between 500 watt and 20,000 watt, such as at approximately 10,000 watt.

In continuation of the fourth example embodiment, a fifth example embodiment additionally provides that first, as explained above, a pulsed inductively coupled plasma 14 is generated in an ICP source 13, using magnetic field support. In this connection, the magnetic field generated by magnetic field coil 21, which was always held constant at least to a great extent with respect to time, in the preceding example embodiments, is also pulsed.

This pulsing of the magnetic field, which is brought about in a simple manner by corresponding current pulses generated by current supply unit 23, may occur in such a way that the magnetic field is only generated if simultaneously also a high-frequency oscillation packet or a high-frequency power pulse for generating or coupling in plasma power into inductively coupled plasma 14 is present at ICP source 13. As long as no plasma power is coupled in or no plasma is excited, generally no magnetic field support may be required either.

A possible synchronization in time of high-frequency power pulses for coupling in plasma power in plasma 14 and current pulses through magnetic field coil 21 is explained, in this connection, with the aid of Figure 4.

The coil current is switched on by magnetic field coil 21 in each case shortly before the application of a high-frequency oscillation packet, i.e., a high-frequency power pulse, and is switched off again after the end of this pulse.

5

Synchronization of current and high-frequency power pulses may be ensured in a simple manner, in this connection, by a conventional impulse generator, integrated into current supply unit 23, for example, which is furnished with additional time elements, in order to connect to the supply the high-frequency power pulse with a certain delay of, for example, 10% of the set high-frequency impulse duration after switching on the current of magnetic field coil 21, or to switch this current off again with a certain delay of, for example, 10% of the set high-frequency impulse duration after the end of the high-frequency power impulse. Such synchronization circuits and corresponding time elements for generating the needed time delays are conventional. For this, current supply unit 23 is further in connection with ICP coil generator 17.

20

Synchronization of the pulsing of magnetic field and coupled-in plasma power may reduce the ohmic heat losses arising in magnetic field coil 21. Thereby the problems of cooling and temperature control are deactivated.

25

If, for example, the coupled-in plasma power is operated with a pulse/pause ratio of 1:20, the current may also be pulsed by the magnetic field coil at, for example, a pulse/pause ratio of 1:18. In this connection, the duration of a current impulse by magnetic field coil 21 is always a little longer than the duration of a high-frequency power pulse.

30

By this procedure, heat removal of magnetic field coil 21 may be reduced, for example, to 1/18 of the original value. Use of electrical energy is correspondingly reduced.

35

Typical rates of repetition or pulse rates are oriented to the inductance of magnetic field coil 21, which limits the speed of change of the coil current. A rate of repetition of a few 10 Hz to 10 kHz is realistic for most magnetic field coils 21, depending on their geometry. Typical pulse/pause ratios for the high-frequency power pulses are between 1:1 and 1:100.

In this connection, the aperture may be applied as described in German Published Patent Application No. 197 34 278 and already explained, below magnetic field coil 21, a few cm above substrate 10 or substrate electrode 11, which carries substrate 10.

The use of this aperture improves, on the one hand, uniformity of the etching over the substrate surface, especially clearly with a symmetrically supplied ICP source 13. At the same time, the time-variable magnetic field - the transients - is also reduced at the location of substrate 10. In this connection, eddy currents in the aperture ring of the aperture lead to a dumping of the time-variable magnetic field components directly before substrate 10, so that induction processes on substrate 10 itself are weakened.

Such changing magnetic fields, so-called transients, may induce voltages in antenna structures on the substrate, which on their part may again lead to damage to the substrate, if the latter, for example, includes integrated circuits or especially field effect transistors.

It is possible also to pulse the high-frequency power, present at substrate 10 via substrate electrode 11, which is generated by substrate voltage generator 12 for the acceleration of the ions. This pulsing may, for example, also be done correlated in time, or synchronized, with the pulsing of the magnetic field and/or the pulsing of the coupled-in plasma power.

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ABSTRACT

A method and device is for etching a substrate, e.g., a silicon element, with the aid of an inductively coupled plasma. For this purpose, a high-frequency electromagnetic alternating field is generated, which produces an inductively coupled plasma from reactive particles in a reactor. In this connection, inductively coupled plasma comes about by the action of the high-frequency electromagnetic alternating field upon a reactive gas. Furthermore, a device, such as a magnetic field coil, is provided which produces a static or timewise varying magnetic field between the substrate and the ICP source. The magnetic field is oriented in such a way that its direction is at least approximately or predominantly parallel to the direction defined by the line connecting the substrate and the inductively coupled plasma.

DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING  
AN INDUCTIVELY COUPLED PLASMA**FIELD OF THE INVENTION**

The present invention relates to a device and a method [which can be carried out with it,] for etching a substrate, [especially] for example, a silicon element, by using an inductively coupled plasma[, according to the species defined in the independent claims].

[Background Information

**] BACKGROUND INFORMATION**

In order to implement an anisotropic high rate etching method, for [instance] example, for silicon, using an inductive plasma source, it is necessary in one method, [known, for example, from DE 42 41 045 C2, to carry out] described, for example, in German Published Patent Application No. 42 41 045, to perform efficient sidewall passivation in as short a time as possible, during so-called passivating steps, and furthermore to achieve as high a concentration as possible of silicon-etching fluorine radicals during so-called etching steps. [Here, in] In order to achieve an etching rate that is as high as possible, it is [obvious] conventional to work with as high as possible [an] a high-frequency power at the inductive plasma source, and thereby to couple in as high as possible plasma powers into the generated inductively coupled plasma.

However, there are limits to these high-frequency powers, which result, on the one hand, from load capacity of the electrical components of the plasma source, but, on the other hand, are also of a process technology nature. Thus, high-frequency powers of an inductive plasma source reinforce harmful electrical intervention by the source region in the

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inductively coupled plasma generated, which deteriorate the etching results on the substrate wafer.

Also, in etching processes according to the kind described in  
5 [DE] German Published Patent Application No. 42 41 045 [C2],  
stability problems appear in the coupling in of the plasma in  
the changeover phases between etching and passivating steps.  
This is based on the fact that, in response to high power to  
be coupled in, in the kwatt range, power reflection and  
10 overvoltage appearing during the changeover phases can have a  
destructive effect on the electrical circuit of the plasma  
source (coil, connected capacitors, generator output stage).

On this point, German Published Patent Application [DE] No.  
15 199 00 179 describes an inductive plasma source, further  
refined compared to the one described in [DE] German Published  
Patent Application No. 42 41 045 [C2], which, with the aid of  
a loss-free symmetrical high-frequency supply of the coil of  
the inductive plasma source, is suitable for especially high  
20 plasma powers, and generates an inductive plasma which is  
particularly poor in electrical interference induced voltages.  
But for this source type [tool], there exists a practicable  
power limit of about 3 kwatt to 5 kwatt, above which the  
required high-frequency components become extremely expensive,  
25 or, with respect to plasma stability, problems take the upper  
hand.

A possible approach towards attaining higher etching rates  
within a manageable power scope is to raise the efficiency of  
30 the plasma generation. In this connection, using magnetic  
fields to raise plasma efficiency is [known in principle from  
the related art] conventional.

By applying a magnetic field to a plasma, as is [well known]  
35 conventional, the electron paths in the plasma are bent, and  
because of that the residence time of the electrons in the

plasma is increased, i.e. the time until they reach a wall which absorbs the electrons, so that each electron can interact more often with surrounding gas atoms until it leaves the effective plasma excitation region. Such impact  
5 interactions between electrons and gas molecules lead to the desired ionization or dissociation of the gas molecules along with the release of radicals needed for the etching process.

According to the related art, a so-called "multipole  
10 confinement" includes a metallic, nonferromagnetic wall having a plurality of permanent magnets of alternating polarity, which reflects electrons from the wall outfitted with these magnets[,] by the action of magnetic fields. Thereby, a higher electron density can be generated within this  
15 "multipole confinement". An analogous RIE (reactive ion etching) source is marketed, for example, by TEGAL Corporation, Petaluma CA 94955-6020, USA, as a so-called "HRe<sup>-</sup> Source".

20 Other [known] conventional plasma source types further make use of a magnetic field having a field direction parallel to a substrate electrode. Thus, by using a kind of Helmholtz coil pair directly at the substrate electrode, a field distribution is generated that is as homogeneous as possible, which leads  
25 [there] to increased length of the electron paths, and thereby to the generation of greater plasma densities. For the further homogenization of the effects, this horizontally oriented magnetic field[,] as, for example, in the MRIE (magnetically enhanced reactive ion etching) equipment of  
30 Allied Materials, Inc., Santa Clara CA 95054-3299, USA, can further be rotated slowly in a planar manner.

In the case of so-called ECR (electron cyclotron resonance) sources, it is [further already known] conventional that one  
35 should tune a longitudinal magnetic field in such a way that the circulation frequency of the electrons in this magnetic

field, the so-called cyclotron frequency, is resonant with the frequency of the [coupled in] coupled-in microwave radiation, at least in a certain volume range of the etching reactor.

Thus, an especially efficient plasma excitation by microwave irradiation can [take place] occur at a sufficiently free path length of the electrons, which opens up to such ECR sources the low-pressure range of process pressures lower than 1  $\mu$ bar as a field of application. In this connection, the low pressure is a necessary condition for a sufficiently great path length of the electrons and for efficient plasma excitation. At higher pressures, ECR sources rapidly become inefficient, and go over to an unwanted thermal plasma generation. The advantage of the magnetic inclusion and the resonant excitation are thereby lost to a considerable extent.

It follows from the formula for the cyclotron frequency  $\omega = eB/m$  that  $B = m\omega/e$ , i.e., at the usually irradiated microwave frequency of 2.45 GHz the magnetic field strength required for cyclotron resonance is 87.6 mTesla.

This application is not simply transferable to the case of high-frequency excitation in the MHz range, i.e., the case of typical frequencies for ICP (inductively coupled plasma) sources, since the free path lengths of the electrons, required for this, assume extremely low, impracticable pressures. After all, an inductive plasma source for high rate etching methods has to be configured for a relatively high pressure range of [ca] approximately 30 to 100  $\mu$ bar.

The usual high frequency of 13.56 MHz, used for inductive plasma excitation using ICP sources, would further, in the case of cyclotron resonance, imply a resonance field strength of only 0.5 mT. However, such a low field hardly has any remaining guidance function for the electrons. For a sufficient guidance function, i.e., suppression of wall losses of the electrons in an extended plasma volume, field strengths

of 10 mTesla or rather several times 10 mTesla to 100 mTesla are required.

Magnetic coils in an ECR-type configuration are also usually placed above, or at the same height as the plasma source, so as to generate the greatest field strength directly at the location of plasma generation, and so as to have the greatest possible influence on the plasma generating mechanism there. In the direction of the substrate to be etched, then, the magnetic field strength decreases rapidly because of the divergence of the magnetic field, so that the guidance function of the magnetic field is no longer sufficiently present in such an arrangement.

Varying plasma power coupled in an inductively coupled plasma having a high-frequency electromagnetic alternating field, adiabatically, between individual method steps, especially alternating etching and passivating steps, is [further known from] described in German Published Patent Application [DE] No. 199 [198 32] 19 832. Such an adiabatic power transition, i.e., a gradual running-up or lowering of the coupled-in plasma power along with simultaneous continuous matching of the impedance of the ICP source to the respective plasma impedance as a function of the coupled-in plasma power, with the aid of an automatic matching network or an impedance transformer ("matchbox"), makes it possible to control the explained problems with regard to power reflection and voltage magnification in response to switching on and off plasma powers in the range of 1 kwatt to 5 kwatt. However, in this connection, a typical duration of transient effects [lies] is in the range of 0.1 sec to 2 sec. Therefore, power changes cannot be made by this approach.

[Summary of the Invention

] SUMMARY

Compared to the related art, the device according to the present invention has the advantage that it makes available a plasma etching equipment having inductive plasma generation or a plasma inductively coupled via an ICP source, in which an additional constant magnetic field, or one varying with time, considerably increases the efficiency of plasma generation. In this connection, the inductively coupled plasma generated, starting from the plasma source, is guided through the generated magnetic field in a kind of magnetic bottle to a substrate to be etched. For this purpose, a magnetic field coil or a sufficiently strong permanent magnet having longitudinal field direction is placed between the inductive plasma source (ICP source) and the substrate or a substrate electrode carrying the substrate, such as a silicon wafer.

Thus, when [carrying out] performing the method according to the present invention, this device effects a very efficient plasma generation in the area of inductive excitation, and a low-loss plasma transport right up to the substrate to be etched. At the same time, decoupling of plasma generation and the generation of the magnetic field is achieved. Because of the symmetry of the [design] configuration of the device according to the present invention, [in spite of] despite the nonhomogeneous field distribution of the magnetic coil, good uniformity on the substrate surface [continues to] may be maintained.

[All in all] Thus, by using the generated longitudinal magnetic field, i.e., a magnetic field [whose] the direction of which is at least approximately or predominantly parallel to the direction defined by the connecting line from the substrate to the inductively coupled plasma, the high-frequency power at the ICP source, required for high rate etching at the highest etching rates, is thus [clearly] reduced by efficient utilization of the coupled-in high-frequency power for generating the desired plasma species

(electrons, ions, free radicals). Because of this, [clearly] higher etching rates are possible at equal plasma power.

5 Because the generation of the longitudinal magnetic field is placed between the ICP source and the substrate, both the substrate and the area of plasma generation in the reactor are arranged in a region of relatively high magnetic field strengths, and, thus, of good guidance of the electrons and ultimately also the ions.

10 In addition, electrical interference effects [coming] from the source region [can] may be effectively reduced by the improvement, achieved with the device according to the present invention, of the economics of the ICP source and the  
15 possibility, that goes with it, of reducing power without reducing the etching rate, or with an etching rate increase at equal plasma power. [On the whole, therefore] Therefore, the etching result is achieved more economically.

20 Furthermore, a power that is constant, pulsed or generally varying with time [can] may be made available considerably more cost-effectively than a greater high-frequency power for coupling in the plasma. This power[, by the way,] demonstrates no harmful effect on the etching process or  
25 components of the plasma etching equipment.

[Advantageous further refinements of the present invention result from the measures indicated in the dependent claims.]

30 Thus, [a particularly advantageous configuration of] the device according to the present invention [comes about if] may include an aperture [is additionally provided,] positioned concentrically with the inner wall of the reactor, which [is preferably] may be arranged [ca] approximately 5 cm above the  
35 substrate positioned on a substrate electrode. Such an aperture construction is [known] described, for example[,

from] in German [patent DE] Published Patent Application No.  
197 34 278.

[It is also advantageous if the] The plasma etching equipment  
5 according to the present invention [is] may also be furnished  
with a balanced, symmetrically [designed] configured and  
symmetrically supplied configuration of the ICP source, as [is  
proposed] described in German Published Patent Application  
[DE] No. 199 00 179.

10 A magnetic field coil having an appertaining current supply  
unit [is particuLarly] may be suitable for generating the  
magnetic field, since with that, the generated magnetic field  
is timely, and, with regard to its strength, is variable and,  
15 in particular, pulsable.

[It is also advantageous if an] An ICP coil generator [is] may  
be provided, which generates a variably adjustable, especially  
periodically varying or pulsed high-frequency power, which  
20 [can] may be coupled into the inductively coupled plasma as  
plasma power.

[It is also very advantageous if components are] Components  
may be integrated into the ICP coil generator which [carry  
25 out] perform a variation of the frequency of the generated  
electromagnetic alternating field, for adapting the impedance  
as a function of the plasma power to be coupled in. An  
automatically acting feedback circuit having a frequency-  
selective component along the lines of a Meissner oscillator  
30 [is particularly advantageously] may be suitable for this.

[Finally, it is very advantageous if the] The pulsing of the  
generated magnetic field [is] may be correlated in time or  
synchronized with the pulsing of the coupled-in plasma power

and/or the pulsing of the high-frequency power coupled into the substrate via the substrate voltage generator.

[Brief Description of the Drawings

5

Exemplary embodiments of the present invention are explained in detail in the following description, using the drawings. The Figures show:

] **BRIEF DESCRIPTION OF THE DRAWINGS**

10 Figure 1 [a very schematic] **is a schematic view of a** plasma etching equipment[,].

Figure 2 **is a schematic view of** an electronic feedback circuit having a connected ICP source[,].

15

Figure 3 **illustrates** an example of a filter characteristic curve[, and].

20 Figure 4 **illustrates** an example of a correlation in time of [high frequency] **high-frequency** power pulses and magnetic field pulses.

[Exemplary Embodiments

] **DETAILED DESCRIPTION**

25 [A] **Figure 1 illustrates a** first [exemplary] **example** embodiment of the present invention [is explained in detail with reference to Figure 1]. A plasma etching equipment 5 [first of all has] **includes** a reactor 15, in [whose] **the** upper region **of which** an inductively coupled plasma 14 is generated  
30 in a **conventional** manner [known per se,] via an ICP (inductively coupled plasma) source 13. The following are also provided here: a gas feed 19 for supplying a reactive gas such as SF<sub>6</sub>, ClF<sub>3</sub>, O<sub>2</sub>, C<sub>4</sub>F<sub>8</sub>, C<sub>3</sub>F<sub>6</sub>, SiF<sub>4</sub> or NF<sub>3</sub>, a gas discharge 20 for removing reaction products, a substrate 10 such as a  
35 silicon body or a silicon wafer to be structured by the



etching method according to the present invention, a substrate electrode 11 which is in contact with substrate 10, a substrate voltage generator 12, and a first impedance transformer 16. Substrate voltage generator 12 also couples in a [high frequency] high-frequency alternating voltage or [high frequency] high-frequency power into substrate electrode 11 and above that into substrate 10, causing acceleration of ions generated in inductively coupled plasma 14 onto substrate 10. The high-frequency power or alternating voltage input in this [way] manner is typically between 3 watts and 50 watts and 5 volts and 100 volts in continuous operation and in pulsed operation respectively, each averaged over time over the pulse sequence.

In addition, an ICP coil generator 17 is also provided, which is connected to a second impedance transformer 18, and above that with ICP source 13. Thus, ICP source 13 generates a high-frequency electromagnetic alternating field and also an inductively coupled plasma 14 composed of reactive particles and electrically charged particles (ions) formed by the action of the high-frequency electromagnetic alternating field on the reactive gas in reactor 15. ICP source 13 [has] includes a coil for this having at least one winding.

Second impedance transformer 18 [is preferably designed] may be configured in the manner described in German Published Patent Application No. 199 00 179, so that a balanced symmetrical [designed] arranged configuration and supply of ICP source 13 over ICP coil generator 17 are obtained. This guarantees [in particular] that the high-frequency alternating voltages applied to the two ends of the coil of ICP source 13 are at least approximately in phase opposition to each other. Furthermore, the center tap of the coil of the ICP source [is preferably] may be grounded, as [indicated] illustrated in Figure 2.

The anisotropic high-rate etching process for silicon, having alternating etching and passivating steps, [known from DE 42 41 045 C2, is further carried out] described in German

Published Patent Application No. 42 41 045, is further

performed, for example, using plasma etching equipment 5.

With respect to further details, known [per se] to one skilled in the art, concerning plasma etching equipment 5, as

described up to this point as being known from the related

art, and the etching method [carried out] performed with it,

especially with respect to the reactive gases, the process

pressures and the substrate electrode voltages in each

respective etching step or passivating step, as the case may

be, [we therefore refer to DE 42 41 045 C2]. reference may be

made to German Published Patent Application No. 42 41 045.

Plasma etching equipment 5[, by the way,] is also suitable for supervisory control, as described in German Published Patent Application [DE] No. 199 27 [806.7] 806.

During the etching of substrate 10, [in particular] for

example, during the passivating steps in reactor 15,

passivating is [carried out] performed, for example, at a

process pressure of 5  $\mu$ bar to 20  $\mu$ bar, and a plasma power, coupled into plasma 14 via ICP source 13, of 300 to 1000 Watt.

C<sub>4</sub>F<sub>8</sub> or C<sub>3</sub>F<sub>6</sub>, for example, are suitable as passivating gases.

During the subsequent etching steps, etching is [done]

performed, for example, at a process pressure of 30  $\mu$ bar to 50

$\mu$ bar and a high plasma power of 1000 to 5000 Watt. SF<sub>6</sub> or ClF<sub>3</sub>, for example, are suitable as reactive gas.

[A preferred] An example embodiment of the plasma etching equipment further provides that, to improve the selectivity of an etching base polymer removal relative to the sidewall film removal, the ion acceleration voltage applied to the substrate by substrate voltage generator 12 be switched back by

reduction of the coupled-in plasma power in the etching steps, each time after breakthrough of the initial etching base polymer, as [has been proposed] described in German Published Patent Application [DE] No. 199 19 832 and explained in  
5 detail.

This switching back here [takes place] occurs in a conventional manner [known per se], either abruptly or continuously via a time-related ramp function. This achieves  
10 a further improvement of the silicon etching rate, of the selectivity of the [etchingprocess] etching process with respect to a masking material, of the profile accuracy and, for example, of the suppression of pockets in a dielectric etch-stop layer.

15 In addition, according to the present invention, a so-called "spacer" is further placed as spacer 22, made of a nonferromagnetic material such as aluminum, between inductively coupled plasma 14 or ICP source 13, i.e. [The],  
20 the actual plasma excitation zone, and substrate 10. This spacer 22 is concentrically set into the wall of reactor 15 as a spacer ring, and thus forms the reactor wall, from place to place. It [has] includes a typical height of [ca]  
approximately 5 mm to 30 mm at a typical diameter of reactor  
25 15 of 30 to 100 cm.

Spacer 22 further surrounds a magnetic field coil 21, which has, for instance, 100 to 300 turns and is wound with a lacquered copper wire of a sufficient gauge for the strength  
30 of current to be used. Additionally, copper pipes [can] may be accommodated in magnetic field coil 21, having cooling water flowing through them so as to remove heat losses from magnetic field coil 21.

Alternatively, it is also possible to wind magnetic field coil 21 itself from a thin copper pipe lacquered with an electrically insulating material, and having the cooling water flowing through it directly.

5

An electric current such as 10 to 100 amp is conducted through magnetic field coil 21 via a current supply unit 23.

10 In the [explained first exemplary] example embodiment, this is, for example, a d.c. current which generates a static magnetic field on the inside of reactor 15, which, in the case of a magnetic field coil 21 having 100 turns and a length of 11 cm as well as a diameter of 40 cm generates a magnetic  
15 field strength in the center of magnetic field coil 21 of about 0.3 mTesla/A of current flow.

For a significant increase of plasma generating efficiency and sufficient magnetic guidance of inductively coupled plasma 14, 10 mT to 100 mT, for [instance] example 30 mT, are required, as [has already been] explained above. That means, [that] current supply unit 23 makes available current strengths of about 30 to 100 amp during etching of a substrate 10, using plasma etching equipment 5.

25

Instead of magnetic field coil 21, [by the way,] a permanent magnet [can] may be used. Such a permanent magnet [advantageously requires] may require no energy, but [has] may have the disadvantage that setting the magnetic field  
30 strength, which is of advantage for setting an optimum etching process, is not possible. [Besides] Furthermore, the field strength of a permanent magnet is temperature dependent, so that magnetic field coil 21 [is] may be preferred.

It is important in each case that the direction of the magnetic field generated by magnetic field coil 21 or by the permanent magnet is at least approximately or predominantly parallel to the direction defined by the connecting line of substrate 10 and inductively coupled plasma 14 or the plasma generating zone (longitudinal magnetic field orientation).

[An advantageous] A refinement of the explained [exemplary] example embodiment further provides for installing an aperture [known from DE] described in German Published Patent Application No. 197 34 278, for improvement of the uniformity of the etching process. For reasons of clarity, this aperture is omitted in Figure 1. It is mounted on the inside of reactor 15, concentrically with the reactor wall, between ICP source 13 or the plasma excitation zone and substrate 10. It [is preferably] may be fastened on spacer 22, [ca] approximately 5 cm above substrate electrode 11 or substrate 10.

Also, in case of the use of a magnetic field coil 21, a suitable monitoring device[, known per se, has to] may be integrated into current supply unit 23, the monitoring device being integrated into the process sequence control, and [carrying out] performing a monitoring of the coil temperature and emergency switching-off, for example, when there is a shortage of cooling water.

In the first [exemplary] example embodiment, during etching, ICP coil generator 17 couples continuously during the etching steps or [the] passivating steps an at least to a great extent constant plasma power of a minimum of 300 Watt to a maximum of 5000 Watt into inductively coupled plasma 14.

[In particular, during] During the passivating steps, a plasma power of 500 Watt, for example, is coupled into inductively

coupled plasma 14, and during the etching steps a plasma power of 2000 Watt, for example, is coupled into inductively coupled plasma 14[;]. ICP coil generator and second impedance transformer 18, in the manner [known from DE] described in  
5 German Published 199 [198 32] 19 832 and explained above, in response to a transition from a passivating to an etching step, [carrying out] performing an adiabatic up-regulating of the coupled-in plasma power over a time-related ramp function and, at the same time, via second impedance transformer 18,  
10 performing an automatic, stepwise or continuous impedance adaptation.

A second [exemplary] example embodiment of the present invention provides that, as a modification of the first  
15 [exemplary] example embodiment, instead of adiabatic control of the high-frequency power coupled into the inductively coupled plasma 14 by IPC source 13, and instead of a matching of the coupled-in [high frequency] high-frequency power given at any point in time, via the automatic matching network  
20 ("matchbox") as the second impedance transformer 18, to the plasma impedance changing with increasing plasma power, alternatively the previously constant frequency of the [high frequency] high-frequency electromagnetic alternating field, which ICP coil generator 17 produces, [should] may be varied  
25 for impedance matching.

The matchbox, [preferably] which may be symmetrically [designed] configured and [supplying] may supply ICP source 13 symmetrically in second impedance transformer 18 [is] may be,  
30 in this connection, [preferably] set in such a way that it ensures an optimum impedance matching in the steady-state power case. This [steady-state power case is characterized in that, in this connection, the plasma power inductively coupled into plasma 14 has reached a high maximum or final value such  
35 as 3000 watt to 5000 watt, a steady-state frequency or a

resonant frequency 1'' of, for example, 13.56 MHz of the frequency produced by ICP coil generator 17 of the [high frequency] high-frequency electromagnetic alternating field having simultaneously been reached.

5

The steady-state frequency [1''] 1' of [customary] conventional ICP coil generators 17 is generally 13.56 MHz, besides this standard, generators having other frequencies or frequency ranges may also [being] be commercially obtainable.

10 However, in such ICP coil generators 17, in deviation from the realization according to the present invention, the steady-state frequency 1'' is set to a fixed value which is, for example, derived with great accuracy from the natural frequency of a quartz-crystal oscillator. Thus, during a power change, for example, during the run-up of the plasma power to be coupled into plasma 14 from, for instance 500 watt to 3000 watt at a steady frequency of the high-frequency of high-frequency alternating field generated by ICP coil generator 17, with a predefined setting of impedance  
15 transformer [17] 18, no matching, or only a [bad] poor one, to the plasma impedance changing as a function of the plasma power is possible, so that high reflected powers appear during the transients. However, if the frequency of ICP coil generator 17 is enabled in such phases, then by a change in  
20 the frequency of the high-frequency electromagnetic alternating field, a substantially optimum impedance adaptation, even under quickly changing plasma conditions, [can] may be maintained.

30 [The essential] An advantage of the production of the correct impedance matching via a variable frequency of the high-frequency power of coil generator 17 is that this frequency change [can] may be [carried out] performed very fast because it is limited only by the control rate of the corresponding  
35 electronic circuit. That makes possible reaction times in the microsecond range, without any problem.

In contrast [to that], manual or automatic setting of an matching network requires the change of mechanical quantities in second impedance transformer 18, for example, the resetting of variable capacitors by motors, which [takes place] occurs correspondingly slowly. Typical time constants here lie in the range of tenths of seconds.

[In a preferred design of] According to the second [exemplary] example embodiment, a control circuit integrated in second impedance transformer 18, for example, in a conventional manner [known per se], detects the instantaneous control error, i.e., the faulty adaptation of the impedance of the output of ICP coil generator 17 and the impedance of ICP source 13, with respect to amplitude and phase. This [takes place preferably] may occur by a measurement of the signal reflected at ICP source 13 or second impedance transformer 18, using reflectometers sufficiently [known from] conventional in high-frequency technology, amplitude and phase errors being detected.

From this information, a corresponding frequency change of the electromagnetic alternating field at ICP coil generator 17, required in each case, is ascertained, [preferably] for example, continuously within a predefined frequency range, so that the control errors with respect to amplitude and phase [can] may be minimized. This basically only corrects an amplitude error, since, as is [well known] conventional, to a great extent only the real plasma resistance changes as a function of the coupled in plasma power, and the phase relationship of the impedances is set correctly, at least roughly, just by the explained presetting of second impedance transformer 18.

When the output power of ICP coil generator 17, and with that also the plasma impedance finally become steady-state after



completion of the run-up of the plasma power, the control circuit takes the frequency of ICP coil generator 17, or of the electromagnetic alternating field generated, back to the actually desired fixed value such as 13.56 MHz, and fixes it there. In this connection, for the frequency in the case of the steady-state power, second impedance transformer 18 is set correctly via the presetting ascertained before, which[, of course,] is a function of the maximum plasma power to be reached, and this can may be done either manually or automatically, using low-speed control characteristics.

To sum up, if the frequency of ICP coil generator 17 is thus fixed, in the steady-state case of the power to be coupled in, at, for example, 13.56 MHz, whereas, during the course of the unstable run-up phases of the generator output power, the frequency is temporarily released within a certain bandwidth, and is controlled by an electronic control system for impedance matching. Thus, it is possible to [carry out] perform even very fast power changes of the generator output power in the range of microseconds in a stable manner, at simultaneous high power changes, which is not possible using known matching networks or impedance transformers.

This is explained, for example, with the aid of Figure 3, in which a filter characteristic line 1' is [represented] illustrated, which [shows] illustrates a preset frequency range within which the frequency of ICP coil generator 17 may be varied, each frequency being assigned a certain high-frequency power or plasma power to be coupled in, or a coupling loss A of the power of ICP coil generator 17. The frequency to be reached in the case of steady-state power, in this connection, is the steady-state frequency 1'', which may be 13.56 MHz, for example, and at which the predefined maximum power is supplied as the plasma power to inductively coupled plasma 14.

[An especially preferable] **A** third [exemplary] example embodiment of the present invention, in continuation of the second [exemplary] example embodiment explained above, further provides leaving the frequency variation of ICP coil generator 17 to an automatically acting feedback circuit, so that one [can] may do without measuring the faulty adaptation in each case or measuring the reflected signals, for example, by reflectometer. This is explained in more detail with the aid of Figure 2.

In this connection, ICP source 13, i.e., its coil, to be exact, in a conventional manner [known per se from DE] as described in German Published Patent Application No. 199 00 179, is first energized by a [preferably], for example, balanced symmetrical matching network 2 from an unbalanced unsymmetrical output of ICP coil generator 17. Adaptation network 2 is a part of second impedance transformer 18.

The ICP coil generator 17 is further, in this case, made [like] similar to a widespread specific embodiment, including a high-frequency power element 3 and a quartz oscillator 4 for producing a high-frequency fundamental wave having a fixed frequency such as 13.56 MHz.

[In the related art] Conventionally, the [high frequency] high-frequency fundamental wave of quartz oscillator 4 is normally supplied to the amplifying input of power element 3. According to the present invention, however, this supply is modified in such a way that quartz oscillator 4 is made accessible separately from the amplifier input of power element 3, and its input is made accessible externally, for [instance] example, via a corresponding input socket. Since the quartz oscillator in this specific embodiment no longer [has] provides a function, it [can actually] may be suitably deactivated.

Power element 3 further [has] includes generator control inputs 9 in a [known way] convention manner, which are used for external control of ICP coil generator 17. Using them makes possible, for example, switching on and off ICP coil generator 17 or the stipulation of a [high frequency] high-frequency power to be generated. In addition, generator status outputs 9' are possible, for the feedback of generator data such as, for instance, generator status current output power, reflected power, overload, etc., to an external control unit (machine control) [not shown], or to current supply unit 23 of plasma etching equipment 5.

The amplifier input of power element 3 is [now] suitably connected to ICP source 13, in the sense of a feedback circuit via a frequency-selective component 1.

In this connection, additionally, capacitors, inductance coils and resistors or combinations of these [can] may be interconnected and provided in a [known] conventional manner as voltage dividers, in order to weaken the high voltages that appear at the coil of ICP source 13 to a suitable measure for frequency-selective component 1 or the amplifier input of power element 3. Such voltage dividers [belong to the related art] are conventional, and are indicated in Figure 2 only by a decoupling capacitor 24 between the coil of ICP source 13 and frequency-selective component 1. Alternatively, one [can] may also move signal tap 25 to the vicinity of the drawn-in grounded center point or center tap 26 of the coil of ICP source 13, where correspondingly lower voltage levels are present. Depending on the distance of the signal tap, which, for example, [can] may be [designed] configured as an adjustable clip contact, from grounded center tap 26 of the coil of ICP source 13, a larger or smaller tapped voltage

[can] may be set, and thus favorable level ratios [can] may be achieved.

Frequency-selective component 1 is represented in the example  
5 as a tunable arrangement of coils and capacitors, so-called LC resonant circuits, which together form a band-pass filter.

This band-pass filter [has] includes as conducting state region a certain predefined bandwidth such as 0.1 MHz to 4 MHz, and a filter characteristic line 1', as [shown]

10 illustrated as an example in Figure 3.

[In particular, the] The band-pass filter has a resonance or steady-state frequency 1'' having maximum signal transmission.

This steady-state frequency 1'' [is preferably] may be 13.56  
15 MHz, for example, and [can] may be fixed exactly, for example, by a quartz-crystal oscillator 6 or a piezoceramic filter element as additional components of the band-pass filter.

Alternatively, it is also possible, instead of LC resonant  
20 circuits, to combine so-called piezoceramic filter elements, or other [known] conventional frequency-selective components [known per se,] into a band-pass filter having the desired filter characteristic line, bandwidth and steady-state frequency 1''.

25 The [set-up] arrangement described above controlled power element 3, matching network 2, ICP source 13 and band-pass filter represents in total a feedback circuit of the same kind as a Meissner oscillator.

30 During operation, this first begins to oscillate in the neighborhood of steady-state frequency 1'', in order to build up to a predefined output power of power element 3. The phase relationship, required for the build-up, between generator  
35 output and signal tap 25 is set correctly for this purpose once, in advance, for example, via a delay line 7 of specific

length, and with that, via the phase shift defined by the signal propagation time or a phase shifter instead of delay line 7. This ensures that the coil of ICP source 13 has damping reduced with a correct phase.

5

Via delay line 7 it is further [especially] ensured that, at the location of ICP source 13, the driving electrical voltage and the current in the coil of ICP source 13 have a resonance phase of approximately  $90^\circ$  to each other.

10

In practice, [by the way,] the resonance condition of the feedback circuit with regard to frequency-selective component 1 is not severe, so that, in general, a small frequency shift in the neighborhood of resonance or steady-state frequency  $1''$  is sufficient for almost automatically correcting the resonance condition with respect to the phase. Therefore, it is sufficient to correct the resonance condition only approximately by the outer circuit elements, so that the resonant circuit builds up somewhere close to its steady-state frequency  $1'''$ .

15

20

However, if all phase shifts from signal tap 25 of the coil of ICP source 13 via the band-pass filter into the input of power element 3, and through the power element back to second impedance transformer 18 into the coil of ICP source 13 should sum up so unfavorably that actually dumping instead of damping reduction of the resonant circuit [takes place] occurs, the system cannot begin to oscillate. The feedback then becomes an unwanted negative feedback instead of the desired positive feedback. The setting of this approximately correct phase is accomplished by delay line 7, [whose] the length of which should therefore be set at one time in such a way that the feedback acts constructively, i.e., to reduce damping.

25

30

35

[All in all] Thus, in the case of faulty adaptation to the plasma impedance, for example, during rapid power changes, the

explained feedback circuit [can] may thus give way in its frequency within the band pass of the band-pass filter, and always maintain a largely optimum impedance matching, even during rapid impedance changes of inductively coupled plasma 14.

Then, as soon as inductively coupled plasma 14 stabilizes with regard to the plasma impedance or the coupled-in plasma power, the frequency of ICP coil generator 17 will return again to near or exactly the value of the maximum pass frequency, which is given by the resonant frequency or steady-state frequency 1''. This matching of the impedance by frequency variation [takes place] occurs automatically and very rapidly within a few periods of oscillation of the [high frequency] high-frequency voltage, i.e., in the microsecond range.

The connection between the output of power element 3 and the input of second impedance transformer 18 is made[, by the way,] by line 8, which is [designed] configured as a coaxial cable, and is capable of carrying a power of a few kwatt.

With this automatically [building up] building-up arrangement, or even with the arrangement described [before] above, having active frequency control for matching to rapidly changing plasma impedances, it is [advantageously] also possible [also] to perform a pulsed operation of the inductive plasma source.

[Now, in] In the case of the refinement of the ICP coil generator described in the fourth [exemplary] example embodiment, it is further possible[ also] to perform a pulsed operation of ICP source 13, and thereby, for example, also to couple in pulsing plasma power during the etching or passivating steps of the etching method.

To do this, the output power of ICP coil generator 17, for [instance] example, is periodically switched on and off using a repetition frequency of typically 10 Hz to 1 MHz, [preferably] such as 10 kHz to 100 [kHz] kHz, i.e., it is pulsed, or the envelope curve of the output voltage of ICP coil generator 17 has its amplitude modulated by a suitable modulating voltage. Such devices for amplitude modulation [are sufficiently well known] conventional from [high frequency] high-frequency technology.

For example, generator control input 9 [can] may be used to select the setpoint value of the [high frequency] high-frequency power of ICP coil generator 17 for the purpose of supplying the signal modulating the [high frequency] high-frequency power of ICP coil generator 17.

Since, in response to a pulsed operation of ICP source 13, very rapid impedance changes appear in plasma 14, [according to the related art up to now,] it is conventionally impossible, especially with power in the kwatt range, to avoid the occurrence of high reflected power during switching on and off coupled-in [high frequency] high-frequency power pulses, or at least to make these harmless.

In contrast, by using the device explained in this [exemplary] example embodiment, the impedance matching of inductively coupled plasma 14, or ICP source 13, and ICP coil generator 17 is ensured at all times, in this case as well.

Compared to a continuous operation, a pulsed operation of ICP source 13 has the further advantage that, during the [high frequency] high-frequency power pulses or during the plasma power pulses a substantially higher plasma density [can] may be achieved than in continuous operation. This is based on the fact that generation of an inductive plasma is a high-

grade nonlinear process, so that the average plasma density in this pulsed operational mode is higher than in the case of an average plasma power corresponding to the time average.

5 Therefore, in pulse operation one effectively obtains more reactive species and ions with respect to the time average than in continuous operation. This is true [especially] when so-called "giant impulses" are used, i.e., relatively brief and extremely high-powered [high frequency] high-frequency  
10 power impulses such as 20 kwatt peak power, as is [now] possible with the device according to the present invention, the average plasma power at time average being [then], for example, only 500 watt.

15 In this connection, unavoidable heat losses in ICP coil generator 17 and other equipment components of plasma etching equipment 5 are [then] correlated with the relatively low time-averaged value of the plasma power, whereas desired plasma effects, particularly the achievable etching rates,  
20 [advantageously] may correlate with the occurring peak powers. As a result, the efficiency of generation of reactive species and ions is [clearly] improved.

In this connection, [of course,] ICP coil generator 17 and the  
25 remaining components of plasma etching equipment 5 involved [have to] may be [designed] configured in such a way that they [can] may process even the occurring peak loads (peak currents and peak voltages) without damage. On account of the high voltage peaks at the inductive coil, the balanced supply of  
30 the ICP coil [has] may have an [especially] advantageous effect on obtaining favorable plasma properties.

A further [considerable] advantage of pulsed operation of ICP source 13 is that interfering electrical charges on substrate  
35 10 to be etched [can] may be discharged during the pauses between the [high frequency] high-frequency power pulses, and



profile control during etching [can] may thereby be improved in toto.

Typical pulse/pause ratios[, by the way, lie] are between 1:1 and 1:100, the average plasma power typically being 100 watt to 1000 watt. The amplitude of the individual [high frequency] high-frequency power pulses effectively [lies] is between 500 watt and 20,000 watt, [preferably] such as at [ca] approximately 10,000 watt.

In continuation of the fourth [exemplary] example embodiment, a fifth [exemplary] example embodiment additionally provides that first, as[ already] explained above, a pulsed inductively coupled plasma 14 is generated in an ICP source 13, using magnetic field support. In this connection, the magnetic field generated by magnetic field coil 21, which was always held constant at least to a great extent with respect to time, in the preceding [exemplary] example embodiments, is [now] also pulsed.

[Especially preferably, this] This pulsing of the magnetic field, which is brought about in a simple manner by [corresponding] corresponding current pulses generated by current supply unit 23, [takes place] may occur in such a way that the magnetic field is only generated if simultaneously also a [high frequency] high-frequency oscillation packet or a [high frequency] high-frequency power pulse for generating or coupling in plasma power into inductively coupled plasma 14 is present at ICP source 13. As long as no plasma power is coupled in or no plasma is excited, [as a rule] generally no magnetic field support [is] may be required either.

A possible [and preferable] synchronization in time of [high frequency] high-frequency power pulses for coupling in plasma power in plasma 14 and current pulses through magnetic field

coil 21 is explained, in this connection, with the aid of Figure 4.

[Here, the] The coil current is switched on by magnetic field coil 21 in each case shortly before the application of a [high frequency] high-frequency oscillation packet, i.e., a [high frequency] high-frequency power pulse, and is switched off again after the end of this pulse.

Synchronization of current and [high frequency] high-frequency power pulses [can] may be ensured in a simple [way] manner, in this connection, by [an] a conventional impulse generator [known per se], integrated into current supply unit 23, for example, which is furnished with additional time elements, in order to connect to the supply the [high frequency] high-frequency power pulse with a certain delay of, for example, 10% of the set [high frequency] high-frequency impulse duration after switching on the current of magnetic field coil 21, or to switch this current off again with a certain delay of, for example, 10% of the set [high frequency] high-frequency impulse duration after the end of the [high frequency] high-frequency power impulse. Such synchronization circuits and corresponding time elements for generating the needed time delays are [in the related art and are generally known] conventional. For this, current supply unit 23 is further in connection with ICP coil generator 17.

Synchronization of the pulsing of magnetic field and coupled-in plasma power [has the great advantage that thereby] may reduce the ohmic heat losses arising in magnetic field coil 21 [can be clearly reduced]. Thereby the problems of cooling and temperature control are deactivated.

If, for example, the coupled-in plasma power is operated with a pulse/pause ratio of 1:20, the current [can] may also be

pulsed by the magnetic field coil at, for example, a pulse/pause ratio of 1:18. In this connection, the duration of a current impulse by magnetic field coil 21 is always a little longer than the duration of a [high frequency] high-frequency power pulse.

By this procedure, heat removal of magnetic field coil 21 [is] may be reduced, for example, to 1/18 of the original value. [At the same time, use] Use of electrical energy is [reduced] correspondingly reduced.

Typical rates of repetition or pulse rates are oriented to the inductance of magnetic field coil 21, which limits the speed of change of the coil current. A rate of repetition of a few 10 Hz to 10 kHz is realistic for most magnetic field coils 21, depending on their geometry. Typical pulse/pause ratios for the [high frequency] high-frequency power pulses [lie] are between 1:1 and 1:100.

In this connection [it is further very advantageous to apply the aperture, known from DE], the aperture may be applied as described in German Published Patent Application No. 197 34 278 and already explained, below magnetic field coil 21, a few cm above substrate 10 or substrate electrode 11, which carries substrate 10.

The use of this aperture improves, on the one hand, uniformity of the etching over the substrate surface, especially clearly with a symmetrically supplied ICP source 13. At the same time, the time-variable magnetic field - the transients - is also reduced at the location of substrate 10. In this connection, eddy currents in the aperture ring of the aperture lead to a dumping of the time-variable magnetic field components directly before substrate 10, so that induction processes on substrate 10 itself are weakened.

Such changing magnetic fields, so-called transients, [could] may induce voltages in antenna structures on the substrate, which on their part [could] may again lead to damage to the substrate, if the latter, for example, [has] includes  
5 integrated circuits or especially field effect transistors.

[As for the rest, it should be emphasized that it] It is [further advantageous] possible also to pulse the [high frequency] high-frequency power, present at substrate 10 via substrate electrode 11, which is generated by substrate voltage generator 12 for the acceleration of the ions. This  
10 pulsing [is then preferably] may, for example, also be done correlated in time, or synchronized, with the pulsing of the magnetic field and/or the pulsing of the coupled-in plasma  
15 power.

## [List of Reference Numerals]

1	frequency-selective component
1'	filter characteristic line
1''	steady-state frequency
2	matching network
3	power element
4	quartz oscillator
5	plasma etching equipment
6	quartz-crystal oscillator
7	delay line
8	line
9	generator control input
9'	generator status output
10	substrate
11	substrate electrode
12	substrate voltage generator
13	ICP source
14	inductively coupled plasma
15	reactor
16	first impedance transformer
17	ICP coil generator
18	second impedance transformer
19	gas supply
20	gas exhaust
21	magnetic field coil
22	spacer
23	current supply unit
24	decoupling capacitor
25	signal tap
26	center tap]

[Abstract

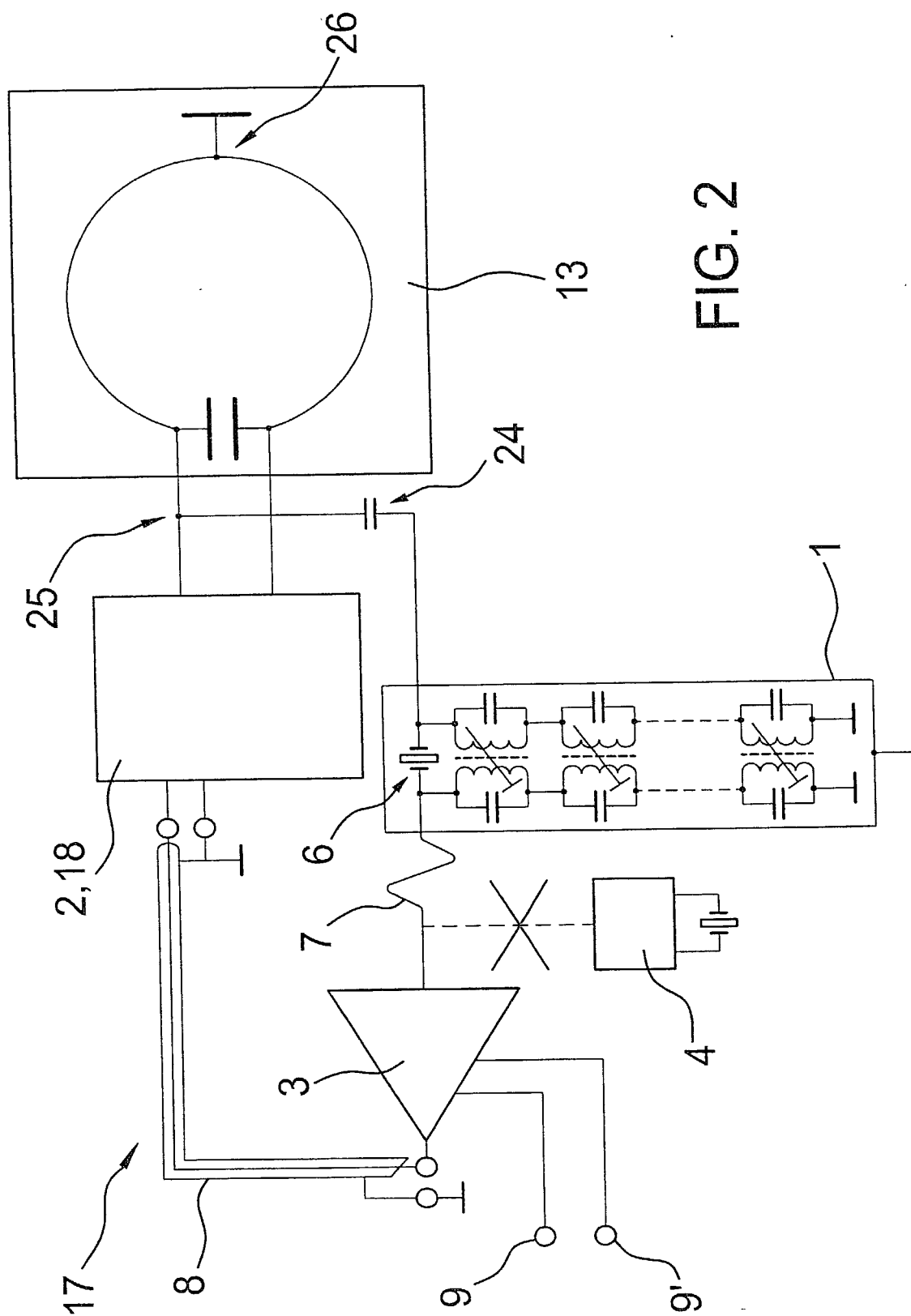
] **ABSTRACT**

A method and a [suitable] device [for carrying out this method is proposed, is for etching a substrate [(10)], [especially] e.g., a silicon element, with the aid of an inductively coupled plasma [(14)]. For this purpose, a [high frequency] high-frequency electromagnetic alternating field is generated, which produces an inductively coupled plasma [(14)] from reactive particles in a reactor [(15)]. In this connection, [the] inductively coupled plasma [(14)] comes about by the action of the [high frequency] high-frequency electromagnetic alternating field upon a reactive gas. Furthermore, a device, [in particular] such as a magnetic field coil [(21)], is provided which produces a static or timewise varying magnetic field between the substrate [(10)] and the ICP source [(13)]. [For this, the] The magnetic field is oriented in such a way that its direction is at least approximately or predominantly parallel to the direction defined by the line connecting the substrate [(10)] and the inductively coupled plasma [(14)]. [

Figure 1]



2/3





3/3

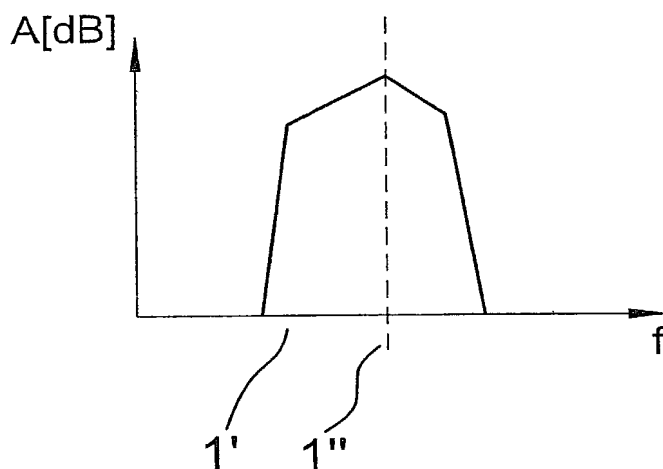


FIG. 3

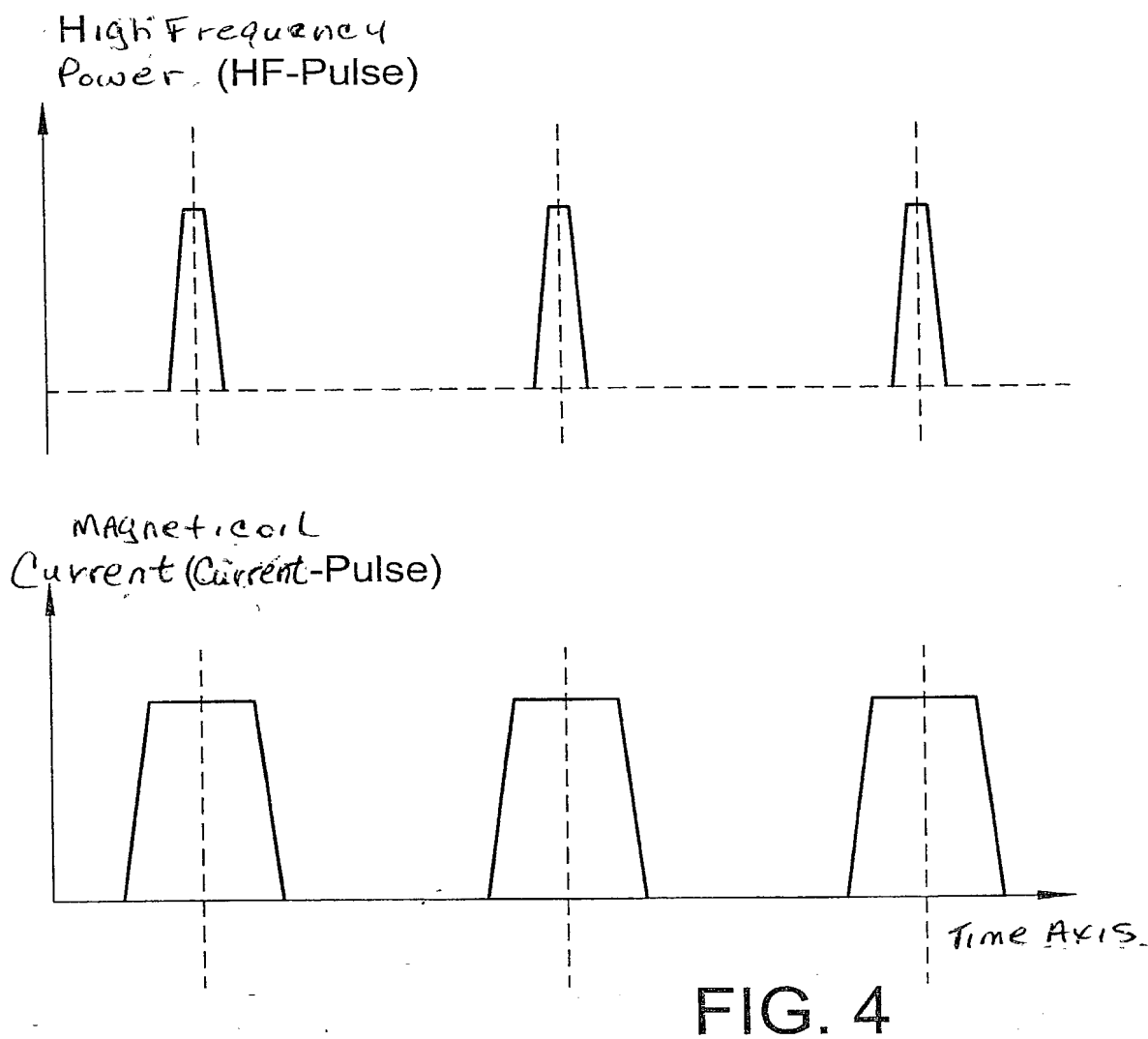


FIG. 4

[10191/2169]

**DECLARATION AND POWER OF ATTORNEY**

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am an original, first and joint inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled **DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING AN INDUCTIVELY COUPLED PLASMA**, the specification of which was filed as PCT International Application No. PCT/DE00/01836 on June 6, 2000.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application(s) for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

**PRIOR FOREIGN APPLICATION(S)**

Number	Country Filed	Day/Month/Year	Priority Claimed Under 35 USC 119
199 33 841.8	Fed. Rep. of Germany	20 July 1999	Yes

And I hereby appoint Richard L. Mayer (Reg. No. 22,490) and Gerard A. Messina (Reg. No. 35,952) my attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful and false statements may jeopardize the validity of the application or any patent issued thereon.

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